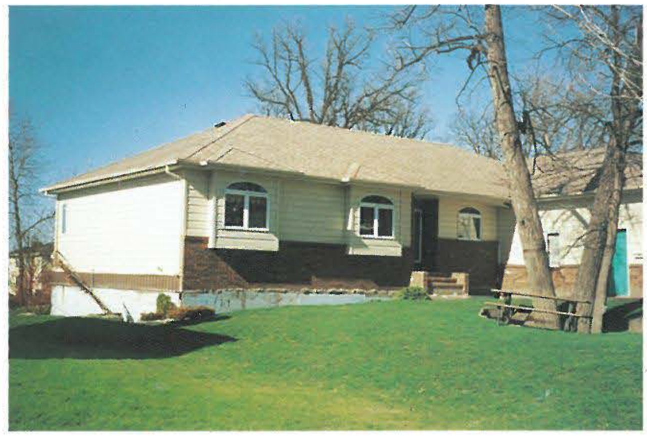
FLOOD PROOFING PERFORMANCE



Successes
&
Failures

US Army Corps of Engineers

NATIONAL FLOOD PROOFING COMMITTEE

Flood Proofing

US Army Corps of Engineers®

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PREFACE

Considerable information on flood proofing exists. This information is generally in the form of brochures, booklets, or reports describing the various flood proofing measures, where the measures should be used, and how to design flood proofed structures. The U.S. Army Corps of Engineers' National Flood Proofing Committee (NFPC) has recognized the need for information that describes how flood proofing measures perform when they are actually tested by floodwater. The NFPC originally solicited such information from Federal and State agencies and other organizations; however, the request resulted in little information. As a result, the NFPC acquired information by visiting various selected flooded areas across the United States. Flood proofed structures located within those flooded areas were inspected to determine the performance of flood proofing measures. The NFPC documented the results of its information-gathering effort into this report, which describes actual flood proofed structures and how floodwater affected those structures. With each specific case described, a "lesson" is presented to briefly describe what worked and what did not.

DATA COLLECTION

Data on 12 floods were collected. The flood locations and dates of these floods are as follows:

Clive, Iowa - May 1986
Central Michigan - September 1986
Crystal City, Minnesota - July 1987
Montgomery County, Texas - May/June 1989
Central Coast, South Carolina - September 1989
St. Louis, Missouri, and Vicinity - Summer 1993
Central Iowa - Summer 1993
Southeastern Texas - October 1994
Florida Panhandle - Fall 1995
Eastern California and Western Nevada - January 1997
Lower Platte River, Nebraska - February 1997
Red River of the North, Minnesota and North Dakota - April 1997

Data collected to date range over a number of years and include both riverine and coastal flooding. Data prior to 1993 were taken from four flood damage assessment reports developed by URS Corporation for the Federal Emergency Management Agency (FEMA). Sites included in these reports have not been visited by a member of the NFPC. Lessons learned from data collected at these sites were developed by an engineer reviewing the data for each structure based on the effectiveness of the flood proofing measures. Subsequent to 1992, all data were collected by the NFPC. Data collection methodology involved keeping informed about

significant flooding events across the United States. Upon the occurrence of flooding, NFPC members placed telephone calls to local Corps of Engineers offices to determine the possibility of flood proofed structures existing in the flooded areas. With the information provided, a decision was made whether or not to visit the flooded area. Not every flooded area across the United States could be visited because of funding limitations, the low possibility of flood proofed structures being present in the flooded area, and the lack of need to inspect and collect data on every flood proofed structure tested by flooding. Initial data collection efforts depended primarily on contacting local officials in selected communities for information on flood proofed structures. This procedure was eventually modified in order to gain more needed information. The procedure evolved to the current procedure: locating the flooded areas, having an experienced engineer drive through the flooded areas searching for flood proofed structures, and visiting with residents of the flooded areas. When a flood proofed structure tested by floodwater was located, the engineer made a personal inspection of the site to determine what worked and what did not in regard to the flood proofing measures.

DATA ANALYSIS

Data analysis was accomplished by an experienced engineer, primarily through analysis of the structure during the onsite inspection and during the subsequent in-office reviews of the data collected. During the onsite field inspection, the engineer looked for reasons why the particular measure was successful or why it failed, if indeed it did fail. In most flood proofing applications where failure occurred, usually only one or two mistakes were made that caused the flood proofing measure to fail.

LESSONS

The "lessons learned" portion of this report is the most important part. The intent of this report is to clearly identify what caused a flood proofing project to either succeed or fail. This is done by making simple statements based on analytical observation rather than rigorous analytical computation. These lessons are summarized in the form of "Do's and Don'ts" of flood proofing.

FUTURE WORK

While a considerable amount of good information has been gathered, more information on successes and failures of flood proofed structures is needed. Information on dry and wet flood proofing measures is especially needed. The NFPC is requesting that any information on flood proofed structures, such as those described in this report, be forwarded to the following individual: Mr. Larry Buss, P.E., U.S. Army Corps of Engineers, ATTN..: CENWO-ED-HB,
215 N. 17th St., Omaha, NE 68102-4978 (e-mail address: larry.s.buss@usace.army.mil). The NFPC intends to continue this project until enough information is obtained to provide an adequate range of successes and failures of all flood proofing measures actually tested by floodwater. This is a national effort, and information is requested from all entities.

PERSPECTIVE

This report documents the performance of flood proofed structures that have been tested by floodwater. As part of this documentation, the report focuses on what components of the flood proofing measure were "key" to the success or failure of the measure. The NFPC quickly found that in many cases more could be learned from a failed measure than from a successful measure. Based on this and the purpose of this report which is to provide as much information as possible to make flood proofing successful, more failed measures are documented than successful measures. This report wants to emphasize that the vast majority of flood proofing measures are successful and that flood proofing is a very viable measure for reducing future flood damage.

REPORT CONTENT

The report is organized into five chapters. **Chapter 1** contains an introduction to flood proofing. It discusses flood proofing objectives; flood proofing measures; and flood, site, and structure characteristics that need to be assessed to implement successful flood proofing.

Chapter 2 contains a very brief description of each observed flood event, structure, and flood proofing measure used, as well as a "lesson." The "lesson" is very important since it points out what worked well and what did not according to the flood proofing measure used.

Chapter 3 contains, in tabular form, the following information on each structure observed:

- Structure number
- Structure location by community
- Structure type
- Flood source (riverine or coastal)
- Flood date
- Flood proofing measure used
- Performance of the flood proofing measure used

Two separate tables showing the above information are presented. Table 1 is listed in order of community and Table 2 in order of flood proofing measure used. This allows rapid location of information by both community and flood proofing measure.

Chapter 4 contains a summary of the "lesson" portion of Chapter 2. It contains the basic "Do's and Don'ts" related to flood proofing. The intent of this chapter is a quick reference of items that must be considered to make a flood proofing measure successful.

Chapter 5 contains a glossary to acquaint the reader with terms used in the report.

CHAPTER 1 - INTRODUCTION TO FLOOD PROOFING

Flood proofing can be defined as "any combination of structural or nonstructural changes or adjustments incorporated in the design, construction, or alteration of individual structures or properties that will reduce flood damages." Simply stated, flood proofing includes any effort property owners may take to reduce flood damage to individual structures and their contents.

FLOOD PROOFING OBJECTIVES

FLOOD DAMAGE REDUCTION. The potential for flood damage is determined by the depth and velocity of flooding and the number of times a structure and its contents may be flooded. Flood proofing a structure will decrease the potential for damage from future floods. Without flood proofing, a structure is subject to damage from all floods that enter the basement or rise above the first-floor level.

Flood proofing can benefit the property owner in several ways. It will save money that would otherwise be spent to repair and clean up the structure and its contents after a flood. In some cases, much or all of the contents, as well as the structure itself, are destroyed. Also, flood proofing will reduce the inconvenience and annoyance caused by the time-consuming process of cleaning up and repairing a structure. Other benefits of flood proofing may include less time off work due to flooding, improved health and safety, peace of mind knowing the frequency of flooding is reduced, and other intangible benefits.

EFFECTIVENESS. All flood proofing measures can be effective in reducing damages from floods for which the measure was designed. However, the only way to ensure complete safety from flood damage is relocating the structure to a site outside of the flood plain. When structures are not removed from the flood plain, floodwaters may rise to an elevation that overcomes any flood proofing measures-- possibly causing damages equal to or perhaps even greater than what would have been caused without flood proofing, unless the flood proofing measure used is elevation. Unless a structure is relocated out of the flood plain, the structure will still be exposed to some potential flood damage even if flood proofed.

SAFETY. Even after flood proofing, a structure in a flood-prone location will still be subject to flooding if floodwaters exceed the design level or cause failure of the flood proofing measures. Property owners must keep this in mind to avoid a false sense of security. No one should remain in a flood proofed structure during a flood, as the flooding could be hazardous and life threatening. High-velocity flows, waves, or other conditions can cause floodwaters to suddenly cause the flood proofing measure to fail, leaving occupants little or no time or ability to vacate the structure and flooded areas. In addition, rising floodwaters may inundate all overland means of escape.

FLOOD PROOFING MEASURES

Flood proofing measures either reduce the number of times the structure is flooded or limit the potential damage to the structure and its contents when it is flooded. There are four general approaches to flood proofing:

- ! Elevating the structure
- ! Relocating the structure
- ! Constructing barriers such as floodwalls or levees to stop floodwaters from damaging the structure
- ! Modifying the structure through flood proofing and relocating contents to minimize flood damage.

ELEVATION. Elevation involves raising such structures as buildings in place so that the lowest floor is above the flood level for which flood proofing protection is designed. The building is raised and set on a new or extended foundation.

Almost any structurally sound building can be elevated. Typically, the least expensive and easiest structure to elevate is a one-story frame building built over a crawl space that is at least 18 inches in height. The process becomes more difficult and expensive as different structures are considered, such as a building with a basement, a slab-on-grade building, a building constructed of brick or block, a multi-story building, or a building with additions.

Property owners wishing to use this method should employ a contractor to ensure that the building is properly raised and a safe foundation is constructed. The elevated foundation must be able to withstand erosion caused by floodwaters, the impact caused by ice and debris in floodwaters, hydrostatic and hydrodynamic force, and impact from high wind velocity and earthquake events. It is also advisable to have the building inspected by a structural engineer prior to elevation to assess the structure’s ability to undergo elevation.

Buildings can be elevated on basically two different types of foundations--an open foundation and a closed foundation. Elevating a building on an open foundation involves raising it onto piers, posts (columns), or piles. If the building is located in an area of coastal flooding, an open foundation is the only way to safely elevate. If the building is subject to high-velocity riverine floodwaters, significant water depths, or potential erosion, the property owner should also consider having the building elevated on an open foundation. Doing so will allow the waters to flow beneath the building and reduce potential damaging impacts. Selection of the proper open foundation (piers, posts, or piles) for various flooding and site characteristics is critical to success. Elevating a building on a closed foundation involves raising it on extended foundation walls or on fill. Elevating on extended foundation walls is very effective where floodwater velocities are low and erosion potential is also low. Elevating on fill is very effective in almost any situation.

Elevation on Extended Foundation Walls. Elevation on extended foundation walls is normally used in areas of low to moderate water depth and velocity. After the building is raised, existing foundation walls can be extended vertically using materials such as masonry block or poured concrete. The building is then set down on the extended walls. While elevating a building on extended foundation walls is often the easiest solution to the problem of flooding, there are several important considerations. The most important concern is that the original foundation and footings must be able to withstand the extra loading, not only from the additional vertical dead load of the new wall but also from the additional flood forces from floodwater against the foundation and from wind forces against the elevated building. If the footings are not deep and wide enough, they may be unable to resist the additional loads, which could result in overturning or undermining of the walls and subsequent collapse. In addition, the original foundation walls may not be wide enough to be extended. A structural or foundation engineer should be consulted to make these determinations.

Depending on the potential flood forces, it will be necessary to reinforce both the footings and the walls using steel reinforcing bars. An equally important concern regarding new foundation wall construction is how it is connected to the existing superstructure of the building. Regardless of what type of extended foundation wall construction is used, hydrostatic and hydrodynamic forces can result in collapse of the structure support system. To eliminate the risk of damage due to hydrostatic force, extended foundation walls need to be constructed with openings or vents to allow floodwaters to enter the enclosed area and equalize the hydrostatic force.

A potential solution to the problem of excessive hydrodynamic force on extended foundation walls is to elevate the building on only two walls, spanning the building between them and leaving the two ends open. By orienting the walls parallel to the flow of water, the amount of wall area resisting the forces from floodwater velocity is less, and loading is significantly reduced. In many cases, the ends are not left totally open. For esthetic or security reasons, it may be desirable to enclose the area. This can be accomplished by installing lattice work or lightweight walls that are designed to break off during floods.

Elevation on Piers. An open foundation support structure is the pier. The piers normally used in flood proofing applications differ from those used in bridge support applications in that a pier for flood proofing consists basically of an upright support member tied to and supported by a reinforced concrete spread footing. This design allows the individual pier to resist lateral movement without the need for cross bracing between the posts as is sometimes needed in a pure post or column design. While they may be the most commonly used type of open foundation for elevating existing structures, they are the least suited for withstanding lateral flood and wind forces. In conventional use, piers are designed primarily for vertical loading. When exposed to flooding, however, they will also experience hydrodynamic forces. Piers used in flood proofing to support an elevated building must be substantial enough to support the structure and also sufficiently reinforced to resist a range of flood and wind forces.

Piers supported by reinforced concrete footings are generally used in shallow-depth flooding conditions with low-velocity flow where scour is not a problem. Piers are normally constructed of either masonry block or poured-in-place concrete. They must have steel reinforcing both in the pier itself and in the footings providing support; the steel reinforcing must be tied together to prevent separation. There must also be a suitable connection between the superstructure and the piers to resist wind and buoyancy forces.

Elevation on Posts or Columns. When flooding is characterized by moderate depths and velocities, elevation of structures on posts (also referred to as columns) is a frequently used flood proofing method. Posts are made of wood, steel, masonry, or precast reinforced concrete. Their ends are set into pre-dug holes, and material such as earth, gravel, crushed stone, or concrete is backfilled around them. Since substantial loading is usually expected, posts are normally anchored into a concrete pad at the bottom of the hole. Care must be taken to ensure that the posts or columns are embedded deeper than any expected scour depth.

While piers are designed to act as individual support units, posts normally must be braced for an additional factor of safety. A variety of bracing techniques, using several different materials, exists. The type to be specifically employed on an elevated structure in a particular area depends on local flood conditions and loads. Some of the more commonly used bracing techniques include wood knee and cross bracing, steel rods, and guy wires.

Elevation on Piles. Where high-velocity flooding can result in scouring, piles provide the best type of foundation. Piles differ from posts in that piles generally are mechanically driven into the ground usually to depths greater than that for posts. Because of this, piles are less susceptible to the effects of high-velocity floodwaters and scouring. Piles must either rest on a support layer, such as bedrock, or be driven deep enough so there is enough friction between the pile and the surrounding soil to carry the load. Piles are generally made of wood, steel, or reinforced precast concrete. They may require bracing similar to the methods described for posts. Because driving piles generally requires bulky machinery, an existing structure that is being flood proofed will have to be temporarily moved aside and set on cribbing until the driving of piles is complete.

Elevation on Fill. This measure is widely adaptable to be successful in almost any situation. The greatest concerns with this measure are erosion of the earthen fill material and settlement of the earthen fill material. The erosion potential can normally be corrected by erosion protection such as riprap. Settlement of the earthen material can be a problem if the structure foundation rests directly on the fill material such as with a slab-on-grade. If this type of foundation is used, an existing structure must be moved to the side temporarily so the fill material can be properly compacted. The best use of this measure is to elevate the structure on extended foundation walls and then place earthen fill material directly against the extended foundation walls. This reduces problems that a stand alone extended foundation wall has such a hydrostatic force, hydrodynamic force, and ice and debris flows.

RELOCATION. Relocating a structure is the most dependable way to flood proof. This method involves moving the structure to another location away from flood hazards. It is the ultimate option for the property owner who wants to be free from the damages, fear, and worry associated with flooding.

This procedure involves raising the structure (e.g., a building), as described in the previous section on "elevation," and placing it on wheels. The building is then transported to a new location and placed on a new foundation.

Property owners should consider many factors before deciding to relocate, including the building's structural soundness and whether there are bridges or other obstructions along the transportation route. During the move of a residential structure, property owners and their families must live elsewhere, perhaps for several weeks, and may need to store furniture and belongings temporarily.

Normally, cost is the major concern associated with building relocation. In addition to paying the moving contractor, the property owner may need to purchase a new lot, build a new foundation, relocate utilities, landscape, and pay for professional services and fees.

FLOODWALLS AND LEVEES (WITH/WITHOUT CLOSURES). Floodwalls and levees are located away from the structure to be protected and prevent the encroachment of floodwaters. They may completely surround the structure or protect only the low side of the property. Unlike other flood proofing measures, a well-designed and constructed freestanding floodwall or levee results in no floodwater forces on the structure itself. Consequently, as long as the floodwall or levee is not overtopped or otherwise failed, the structure is not exposed to damaging hydrostatic or hydrodynamic forces. With these kinds of measures, there is no need to make structural alterations to the building or structure to be protected. These measures require installation of a sump pump to enable seepage water flowing through or under the levee or floodwall, and rainwater falling inside the levee or floodwall, to be evacuated prior to damaging the protected structure.

Floodwalls and levees require periodic maintenance, including the removal of debris from any check valves on pump discharge pipes after each storm and inspection of the sump pump for proper operation. In addition, the property owner will need to inspect levees for signs of erosion, settlement, animal burrows, and trees. Floodwalls need inspection for signs of cracking and spalling. Care must be taken when constructing floodwalls and levees to protect other properties from any adverse impacts, to avoid filling in wetlands, and to maintain regulatory floodways.

While it is possible to design floodwalls and levees for large flood forces associated with major flood protection projects, such flood proofing measures for individual structures are generally restricted to a height of 6 feet or less. This restriction is usually necessary because of limited space, cost, visual concerns, and less complex design analysis.

The most important consideration of all is that property owners who have constructed floodwalls or levees should not have a false sense of security about their property protection. Every flood is different and one that exceeds the design height and overtops the floodwall or levee or breaches the floodwall or levee can happen at anytime. For this reason, the protected area should always be evacuated prior to flooding.

If a floodwall or levee fails due to overtopping, damage to the protected structure will be as great or greater than if no protection had been provided. Additional damage could even result because of the longer time it takes to remove floodwater from the inside of the floodwall or levee once flood levels subside.

Levees. Typically, levees are constructed of compacted fill taken from locally available soils. Depending on the availability of suitable local soils, levees may be one of the least expensive of all flood proofing measures. They are usually built parallel to the river and extend to high ground when it is available. They can also be built to completely surround the structure to be protected. Because they are easy to shape, levees can be made compatible with the landscape. If enough space is available, they can have broad bases and rounded tops to blend in with the surrounding landscape. The property owner can plant grass and other forms of light vegetation on an earthen levee to help prevent erosion and provide esthetic enhancement. Compacted earth can also be placed against a building in lieu of a free-standing levee and pleasingly landscaped. This could be considered a dry flood proofing technique.

Levees have drawbacks that may make them impractical for many property owners. One potential problem is that levees can impede the natural flow of water in a flood plain, possibly resulting in increased flooding of adjacent property. Similarly, they can also block the natural drainage from surrounding property. Another major drawback is that levees take up a considerable amount of property space. To minimize erosion and to provide adequate stability, their embankment slopes must be no steeper than a ratio of one vertical to two horizontal--with a ratio of one vertical to three horizontal preferred. Because of this, a levee’s width will be several times its height.

An important factor in determining the feasibility of a levee involves the availability of suitable fill material for the levee as well as the adequacy of the underlying soil that must support the levee. Most types of soils are suitable for constructing levees. The exceptions are very wet, fine-grained, or highly organic soils. The best soils are those that have a high clay content and therefore are highly impervious. Impervious soils minimize seepage problems either through or under the levee system.

In those cases where suitable fill material is not locally available, the expense of transporting appropriate material to the site can be significant. This additional cost could be a major factor in determining the economic feasibility of this measure. While all levee slopes should have vegetative cover, one way to further protect a levee from erosion is to armor the vulnerable areas with resistant material such as stone riprap.

Floodwalls. Similar to levees, floodwalls also keep water away from the structure being protected. However, floodwalls are constructed of stronger materials and take less space. Floodwalls can be constructed using a variety of designs and materials and can be constructed not only to protect a building but also to enhance its appearance.

Selection of a floodwall design is primarily dependent on the type of flooding expected at the structure site. Large flood depths and high flood velocities create large hydrostatic and hydrodynamic forces that could cause a floodwall to fail by tipping over. High flood velocities, combined with erosive soil, can also cause floodwall failure due to scour beneath the footings of the floodwall.

Closures. Closures must be provided for sidewalks, driveways, and other openings left in a floodwall or levee. However, floodwalls and levees designed without closures are more reliable because there is no need for human intervention to properly install the closure device in the openings. In the case of a levee, access may be provided simply by constructing the levee with gentler sideslopes at the driveway to allow vehicles to enter and exit by passing over the levee. When constructing a floodwall or levee around a structure, a sump pump must be incorporated into the design to provide proper interior drainage of floodwater seepage under or through the levee or floodwall and of rainwater falling on the protected side of the levee or floodwall.

Closures serve to close the openings in floodwalls and levees and prevent water from entering. They can consist of a variety of shapes, sizes, and materials. In some cases, closures are permanently attached using hinges so they can remain open when there is no flood threat. They may also be portable, normally stored in a convenient, nearby location and slipped into place when a flood threatens. There are a number of elements involved in designing and using a closure system. Closures can be separated into two basic categories: permanent or temporary. Combinations of permanent and temporary closures may also be feasible. Permanent closures are those that permanently close openings such as little-used doorways or windows. Temporary closures are those that are put into position to close an opening during a flood event and are then removed and stored away after the event.

Temporary closures can be considered an option only if a flooding situation provides sufficient warning time to properly install them. Both sufficient warning time and “human intervention” are critical to the success of closures since all temporary closure systems require personnel to install them and make certain they are properly sealed.

Closures that are stored between floods must be readily accessible. The effectiveness of an entire system will be compromised if the closures are stored such that flooding renders them inaccessible or if even one closure is improperly installed. Closure systems are most effective where there are a limited number of openings. If there are too many, leakage could overwhelm and defeat the system. Any sewers or drain pipes passing through or under a floodwall or levee will require closure valves to prevent backup and flooding inside the protected area. Care must also be taken to ensure

that backfill material placed to cover utility access under or through a levee or floodwall is properly compacted so floodwater cannot breach the levee or floodwall.

DRY FLOOD PROOFING. Dry flood proofing involves sealing the walls of structures such as buildings with waterproofing compounds, impermeable sheeting, or other materials and using closures for covering and protecting openings from floodwaters. In areas of shallow, low-velocity flooding, closures in the form of shields can be used on doors, windows, vents, and other building openings. The first step in using closures placed directly on buildings is to be certain that both the closure and the building are strong enough and sufficiently watertight to withstand flood forces. To prevent backup and flooding inside a building, sewer lines should be fitted with cutoff or check valves that close when floodwaters rise in the sewer. Utility lines through the flood proofing measure also need to be designed so floodwaters cannot fail the flood proofing measure by following the utility line into the protected area.

Dry flood proofing is not generally recommended for buildings with basements. These types of structures are susceptible to large amounts of hydrostatic force if the ground surrounding the basement becomes saturated with water. This can result in serious damage to the structure due to uplift of the basement floor, collapse of the basement walls, or the entire structure becoming buoyant. Generally, dry flood proofing should only be employed on structures constructed of reinforced concrete, concrete block, or brick veneer on a wood frame. Weaker construction materials will fail at lower water depths from hydrostatic force. Conventionally constructed brick veneer on a wood frame or concrete block walls should not be flood proofed above a height of 3 feet because of the danger of structural failure from hydrostatic forces. Dry flood proofing above this height is not recommended unless the building walls are designed for larger hydrostatic force.

Some waterproofing compounds cannot withstand significant water pressure or may deteriorate over time. For effective dry flood proofing, a good drainage system must be provided to collect the water that leaks through the sealant or sheeting and around the closures to the interior of the structure. These systems can range from small wet-vacuums to a group of collection drains running to a central point from which water is removed by a sump pump. A perimeter drainage system leading to an adequate sump pump or pumps must be installed if an effort is made to flood proof a basement. This is needed in order to reduce hydrostatic force on the basement floor and walls. Property owners considering dry flood proofing should consult a professional engineer to analyze hydrostatic force that can cause structural damage to walls and floors. Though dry flood proofing may seem simple, it is a sophisticated method that requires full understanding of the possible dangers stemming from poor planning, design, or installation. Because it may be difficult to reliably evacuate seepage water and also to refrain from occupying a building during a flood event, this measure may be less easy to satisfactorily accomplish.

Most wall materials, except for some types of high-quality concrete, will leak unless special construction techniques are used. These techniques require a high level of workmanship if they are to

be effective. The most effective method of sealing a brick veneer wall is to install a watertight seal behind the brick when the building is constructed. To flood proof existing brick veneer structures, the best way to seal a wall is to add an additional layer of brick veneer with a seal "sandwiched" between the two layers. It is possible to apply a sealant to the outside of a brick, block, or concrete wall, but any coating must be applied carefully. Cement or asphalt-based coatings are the most effective materials for sealing such walls, while clear coatings such as epoxies and polyurethanes tend to be less effective. As a result, the esthetic advantages of brick veneer walls are lost with the use of better sealant coatings.

The difficulty and complexity of sealing a structure also depend on the type of foundation, since all structural joints, such as those where the walls meet foundations or slabs, require treatment. For very low flood levels, such as a few inches of water, a door can be flood proofed by installing a waterproof gasket and reinforcing the door jamb, hinge points, and latch or lockset and coating it with a waterproof paint or sealant.

If there is a chance of higher flood levels, some type of closure shield will be needed. If the expanse across the door is 3 feet or greater, the shield will have to be constructed of strong materials, such as heavy aluminum or steel plate. The frame for such an installation must be securely anchored into the structure. When windows are exposed to flooding, some form of protection is needed because standard plate glass cannot withstand flood forces. One solution is to brick up all or part of the windows. It may also be possible to use glass block over the windows instead of brick, to admit light. For normal-sized windows, shields can also be used. They should be made of such materials as strong Plexiglas, aluminum, or framed exterior plywood. These can be screwed to the building or slid into predesigned frame slots in order to cover the windows. Another alternative is to replace the glass with heavy Plexiglas; however, the window must be sealed shut and waterproofed using water-resistant caulking.

WET FLOOD PROOFING. If dry flood proofing is impossible or too costly, another option is wet flood proofing, which allows the structure to flood inside while ensuring there is minimal damage to the building and any contents. Interior flooding allows hydrostatic force on the inside of the building walls to equally counteract the hydrostatic force on the outside, thus eliminating the chance of structural damage. When the structure is designed for wet flood proofing, vulnerable items such as utilities, appliances, and furnaces should be relocated or temporarily waterproofed with plastic bags and sheeting. Utilities and appliances should be moved permanently or temporarily to a place in the building that is higher than a selected flood level--either to an existing area, such as the attic, or to a small addition that could serve as a utility room.

If there is no space for relocating utilities, appliances, and other contents, they may be protected in place. In the case of very shallow flooding, a mini-floodwall built around these items would provide protection. For deeper waters, they could be elevated on platforms or suspended overhead from floor or ceiling joists.

The property owner must have sufficient warning time to employ wet flood proofing methods by temporarily moving items and then to evacuate all personnel prior to flooding. If a building is subject to flash floods, this method will not work. In addition, the property owner must be aware that flooding an area containing a source of electricity or hazardous materials can be dangerous. Also, cleanup will be required after each flood.

The owner of a building that has been wet flood proofed may choose to flood the basement of that building with a clean, potable water source (such as water from a garden hose connected to a faucet) before floodwaters reach the building. This would reduce the amount of contaminated floodwaters entering the structure and would minimize health concerns, cleanup time, and costs.

CHARACTERISTIC ASSESSMENT FOR SUCCESSFUL FLOOD PROOFING

FLOODING CHARACTERISTICS.

Flood Depth. A structure is susceptible to floods of various depths, with floods of greater depth occurring less frequently than floods of lesser depths. Potential flood elevations from significant flooding sources are shown in flood insurance studies (FIS) for communities participating in the National Flood Insurance Program (NFIP) and in other sources of flood plain information. For the purpose of assessing the depth of flooding likely to impact a structure, it is convenient to use the flood levels shown in FIS's, historical flood levels, and/or flood information from other studies and reports. The depth of flooding affecting a structure can be calculated by determining the height of the flood above the ground elevation at the site of the structure.

If a structure such as a building is subject to flooding depths greater than 3 feet, elevating or relocating the structure are the most effective measures of flood proofing. Dry flood proofing is not appropriate because water depths greater than 3 feet may cause hydrostatic force large enough to render structural damage or cause wall collapse unless the building has been designed to accommodate such forces. Flood proofing with levees and floodwalls for depths greater than 3 feet can be undertaken, but it may require devices to control seepage under the levee or floodwall.

If a structure subject to flooding depths less than 3 feet is well constructed by conventional methods, hydrostatic force is not a problem. Therefore, consideration can be given to using barriers, sealants, and closures for flood proofing. If shallow flooding causes a basement to fill with water, wet flood proofing can be used to reduce flood damage. Special devices are available to prevent basement flooding due to water backup through sewers.

Flood Velocity. The speed at which floodwaters move--the floodflow velocity-- is normally expressed in terms of feet per second (fps). As floodwater velocity increases, hydrodynamic forces are added to the hydrostatic forces from the depth of still water, significantly increasing the

possibility of structure failure. Greater velocities can quickly erode or scour the soil surrounding structures. These fast-moving waters can also result in failure by erosion, and their impact may move a structure from its foundation. When floodwater velocities exceed 3 fps and 3 feet of depth, it becomes difficult, if not impossible, for adults to maintain their balance while walking through a flooded area. Unfortunately, there is usually no readily available source of information to determine potential flood velocities in the vicinity of specific structures. Historical information from past flood events is probably the most reliable source. If personal knowledge of past flood erosion and/or movement of structures is not available, others in the neighborhood may be able to provide this type of information. If specific information on flood velocities is available and indicates that the structure is subject to floodwaters with velocities greater than 3 fps, professional advice is critical in the selection of an appropriate flood proofing measure.

Flash Flooding. In areas of steep topography and/or small drainage areas, floodwaters can rise very quickly with little or no warning. This condition is known as flash flooding. High velocities usually accompany flash flooding and may preclude certain types of flood proofing. In a flash flooding situation, flooding usually begins to occur within 1 hour after significant rainfall. If a structure is susceptible to flash floods, insufficient warning time can preclude the use of any flood proofing method requiring human intervention, such as installing closures on windows, doors, or floodwalls. Temporarily relocating moveable contents to a higher level is also impractical. However, these methods can be effective if a building is not subject to flash flooding and the area has an adequate flood warning system and such warnings are broadcast on television and radio or disseminated on a personal basis by local emergency authorities. In areas of long-duration flooding, certain methods such as dry flood proofing may not be as applicable because of the increased chance for seepage and failure due to prolonged exposure to floodwater.

Ice and Debris Flow. In colder climates, chunks of ice from ice breakup can be carried in floodwaters and act as a battering ram, causing serious structure damage. During flood periods with freezing temperatures, ice can also form around the structure. If floodwaters rise and the ice is thick enough and attached well enough to the structure, lifting can occur, causing severe damage. Floodwaters often carry debris, such as boulders, rocks, and trees, that can destroy most flood proofing measures as well as the structure itself. This type of floodflow is called a mudflow, debris flow, or a mudflood, depending on the quantity of sediment/debris in the floodwater.

If a structure is subject to ice or mudflow/debris flow, flood proofing measures involving elevation other than on earthen fill require the services of a professional engineer to ensure that the building structural supports can withstand the impact of ice or debris flow. Dry flood proofing and wet flood proofing measures should not be used if the building is in an area of ice and debris flow. Floodwalls or levees can be used to protect against this type of hazard if properly designed. Relocation is always applicable for mitigating this type of hazard.

SITE CHARACTERISTICS.

Site Location. Coastal flooding is normally caused by such large storms as hurricanes that cause hazards due to waves, storm surge, abnormally high tides, heavy rainfall, beach erosion, etc. Normally, plenty of warning time exists. High tides, coupled with wave action from high winds, often cause damage more severe than that brought on by river or lake flooding. If a structure is subject to coastal flooding, elevation on piles or posts (preferably piles) or relocation are the only feasible flood proofing measures. The destructive force of wave action will generally destroy other types of flood proofing.

Riverine flooding results from heavy or prolonged rainfall, snowmelt, or combined runoff from the drainage area. Hazards from riverine flooding are based on flood depth, flood duration, flood velocity, erosion, and ice and debris. Warning time can vary from minutes to weeks.

Depending on the characteristic of the flooding source and flood, all flood proofing measures are applicable.

Soil Type. Permeable soils, such as sand, are those that allow groundwater to flow freely. If a structure such as a building has a basement and is located on permeable soil, flood proofing measures involving sealants and closures are ineffective because the permeable soil will allow groundwater to increase hydrostatic force on the basement walls, causing seepage and/or structural damage. Water will pass under floodwalls and levees constructed on permeable soil unless seepage control measures are included as part of the flood proofing measure. Other problems with soil that is saturated with floodwaters also need to be considered. If a structure is located on unconsolidated soil, wetting of the soil may cause uneven (differential) settlement. The structure may then be damaged by inadequate support and pulling or bending forces. Some soils may expand when exposed to floodwater and cause forces against basement walls and floors. Thus, serious damage can occur even though floodwaters do not enter the structures.

STRUCTURE CHARACTERISTICS.

Structure Foundation. There are three basic types of foundations for structures such as buildings which may be utilized individually or in various combinations. They are slab-on-grade; crawl space with the structure supported on extended foundation walls, piers, posts (columns), or piles; and basements with poured concrete walls and floors or masonry walls and poured concrete floors. Each type of foundation has its own advantages and limitations when flood proofing measures are being evaluated. All types of flood proofing can be considered for slab-on-grade foundations and crawl spaces on extended foundation walls. However, the crawl space foundation generally provides for more economical elevation and relocation flood proofing measures. Structures with basements require more involved flood proofing measures and are generally not recommended for flood proofing.

Structure Construction. Most structures are constructed of concrete and masonry or wood. However, other materials such as steel, aluminum, vinyl, and fiberglass are also used. Combinations of these materials may be used in the construction of a single structure. Thus, the suitability of applying a specific flood proofing measure can be difficult to assess. Concrete and masonry construction can be considered for all types of flood proofing measures. When classifying construction as concrete and masonry, it is important that all walls and foundations be constructed of the material. Otherwise, there may be a weak link in the flood proofing measure, resulting in potential for failure.

Structure Condition. Structure condition may not be easy to evaluate, as many structural defects are not readily apparent. However, careful inspection of the property should provide for a classification of "excellent to good" or "fair to poor." This classification is only for the reconnaissance phase of selecting an appropriate flood proofing measure(s). More in-depth investigation and design may alter the initial judgment regarding building condition and eliminate consideration of some flood proofing measures.

FLOOD PROOFING MATRIX

A flood proofing matrix (Figure 1) has been included in this report to better understand the relationship of flood characteristics, site characteristics, and structure characteristics to the applicability of particular flood proofing measures. The matrix serves to summarize the information presented in this chapter.

Instructions for using the

FLOOD PROOFING MATRIX

STEP 1 Select the appropriate row for each of the nine characteristics that best reflects the flooding, site, and building structure characteristics.

STEP 2 Circle the N/A (not applicable) boxes in the rows of characteristics selected.

STEP 3 Examine each column representing the different flood proofing measures. If one or more N/A boxes are circled in a column representing a flood proofing measure, that alternative should be eliminated from consideration unless special features (as footnoted) are applied to overcome the N/A concern.

STEP 4 Test the flood proofing measures that do not have circled N/A boxes for compliance with your community's flood plain management ordinance and building permit requirements.

STEP 5 Flood proofing measures that would be in compliance with community requirements should now be further evaluated for economic, aesthetic, risk, and other considerations. A preferred measure should evolve from this evaluation.

STEP 6 Obtain professional engineering and construction services for detailed design and implementation of the preferred flood proofing measure. Professional advice may rule out the preferred measure, and an alternate measure will need to be selected.

N/A[2] Dry flood proofing can work with these depths if the walls and floor are designed to resist the hydrostatic force and if the structure is designed to not become buoyant.

N/A[3] Space and aesthetics usually limit levee and floodwall heights for flood proofing to 6 feet. However, from an engineering viewpoint, greater heights are common.

N/A[4] Hydrodynamic force directly on the structure eliminates this measure.

N/A[5] Scour due to fast flood velocity eliminates this measure.

N/A[6] Flash flooding does not allow time for human intervention; thus, these measures must perform without human activity involved. Openings in foundation walls must be large enough to equalize water forces and should not have removable covers. Closures and shields must be permanently in place, and wet flood proofing cannot include last-minute modifications.

N/A[7] Permeable soils allow seepage under floodwalls and levees; therefore, some type of cutoff feature would be needed beneath structures. Permeable soils also allow hydrostatic force to directly affect the structure; therefore, the walls and floor must be designed to resist hydrostatic force and buoyancy.

FLOOD PROOFING MATRIX		FLOOD PROOFING MEASURES									
		Elevation on Foundation Walls	Elevation on Piers	Elevation on Posts or Columns	Elevation on Piles[1]	Elevation on Fill[1]	Relocation	Floodwalls and Levees	Floodwalls and Levees with Closures	Dry Flood Proofing	Wet Flood Proofing
FLOODING CHARACTERISTICS	**Flood Depth**										
	Shallow (less than 3 feet)										
	Moderate (3 to 6 feet)									N/A[1]	
	Deep (greater than 6 feet)							N/A[2]	N/A[2]	N/A[1]	
	Flood Velocity										
	Slow (less than 3 fps)										
	Moderate (3 to 5 fps)	N/A[3]								N/A[3]	N/A[3]
	Fast (greater than 5 fps)	N/A[3/4]	N/A[4]							N/A[3/4]	N/A[3/4]
	Flash Flooding										
	Yes (less than 1 hour)								N/A[5]	N/A[5]	N/A[5]
	No										
	Ice and Debris Flow										
	Yes	N/A								N/A	N/A
	No										
SITE CHARAC-TERISTICS	**Site Location**										
	Coastal Floodplain	N/A	N/A					N/A	N/A	N/A	N/A
	Riverine Floodplain										
	Soil Type										
	Permeable							N/A[6]	N/A[6]	N/A[6]	
	Impermeable										
BUILDING CHARACTERISTICS	**Building Foundation**										
	Slab on Grade										
	Crawl Space									N/A	
	Basement		N/A	N/A	N/A					N/A	
	Building Construction										
	Concrete or Masonary										
	Metal										
	Wood										N/A
	Building Condition										
	Excellent to Good										
	Fair to Poor	N/A	N/A	N/A	N/A	N/A	N/A			N/A	N/A

1> For an existing structure, the structure must be temporarily relocated to place fill and piles

CHAPTER 2 - FLOOD PROOFING PERFORMANCE

This chapter presents in narrative form information on how flood proofing measures performed when tested by flooding. The information presented was gathered by an experienced engineer who viewed the structures and the flood proofing measures after they were subjected to floodwater. The structures are numbered in accordance with the numbering system used in Tables 1 and 2 of Chapter 3. A short discussion of the flood event precedes each respective group of structures. Photographs of individual structures or flood proofing measures are shown if they were available and if they were considered to be of value in understanding why the flood proofing measure either was successful or failed.

CLIVE, IOWA

On the evening of May 9, 1986, an intense short-duration thunderstorm west of Clive, Iowa, resulted in flash flooding along Walnut Creek. There was little warning to residents of rising floodwaters. Velocities were only significant near the creek, and debris was not a problem. A prolonged wet period prior to the flood had saturated the soil. The typical soil profile of the area around the structure is a clay loam over a sand strata.

STRUCTURE 1. This house had a full basement. The walls were reinforced concrete with 2 feet exposed above the soil. The house was elevated some with fill placed around the house to promote runoff away from the home. This house was considered to be dry flood proofed. No structural or water damage occurred to the house; however, scour resulted in a soil loss of approximately 3 feet at an above-ground pool adjacent to the creek.

Lesson. The flood proofing system worked even though the area soils were saturated prior to the flood event. Damage from hydrostatic force did not occur to the basement walls because the walls were reinforced, the walls were not totally below "normal" grade (because fill had been placed around the house), and the flood event was very short.

CENTRAL MICHIGAN

Beginning September 10, 1986, and lasting until September 12, 1986, 13 inches of rain fell over central Michigan. This rainfall resulted in flooding that lasted 48 hours and longer in some areas.

ALMA, MICHIGAN

STRUCTURE 2. A local convenience store with its back facing the Pine River was flood proofed with 2-foot-high steel floodshields in place at doorways to protect against the 100-

year flood. Flood proofing had been incorporated into the design of this building, which had a slab-on-grade foundation and masonry walls, in order to meet local building requirements. As part of the flood proofing system, the external utilities had been elevated on timber posts.

The flood of September 1986 overtopped the floodshields by 6 to 9 inches. This resulted in 3 feet of water entering the building and causing extensive damage to the contents of the store. No structural damage occurred. At the external utilities, scouring occurred at the base of the timber posts that supported the utilities because the end of the downspouts from the roof gutters were improperly located. Also, no splash aprons were provided at the outlet of the downspouts. Continued scour could have resulted in premature loss of the utilities, depending on the depth of post embedment.

Lesson. An apparent insignificant item such as downspout location threatened the utility supports and could have caused utility failure if the post embedment depth had been too shallow. The main flood proofing system failed because of inadequate design height, which allowed the measure to be overtopped. Higher floodshields may have provided protection; however, had they been higher, the hydrostatic force against the walls of the building may have exceeded the design and caused structural failure of the building walls.

MIDLAND, MICHIGAN

STRUCTURE 3. This structure represents several buildings that had basements with no windows and were considered to be "dry flood proofed.” These structures were flooded by backwater from the Tittabawase River. Flood marks matched, within a few inches, the 100-year flood from the published flood insurance study (FIS). Velocity was not a factor, as neither hydrodynamic loads nor impact loads caused any damage. Floodwater depths were less than 2 feet, and the structures were inundated for about 2 days. Floodwater was against each structure. The primary variable in whether or not structures were damaged was the basement wall material. Of the 10 buildings generally inspected, 6 had concrete block walls (5 of which were damaged) and 4 had poured concrete walls (2 of which were damaged).

Lesson. Because the buildings had no basement openings, floodwaters could not enter the buildings and equalize hydrostatic force. Much of the surrounding soil was clay, which expanded when it became saturated. The hydrostatic force caused the ultimate damage and failure of the measure. It should noted that the poured concrete walls sustained less damage than the concrete block walls.

STRUCTURES 4, 5, 6. These structures had basements with concrete block walls. Two structures failed along the rear basement wall, where the longest unsupported horizontal spans occurred. The other structure failed along the front basement wall, where the wall was not connected to the sill plate. When this front wall failed, it allowed water to enter, resulting in unequal force on the interior partition walls and causing the partition walls to fail. Another

resident in the area with similar basement construction prevented damage to his structure by filling the basement with water to counteract the external hydrostatic force.

Lesson. It is very difficult to satisfactorily flood proof a basement if floodwater comes in contact with the foundation walls. Basements should not be considered to be dry flood proofed unless the foundation walls and basement floor have been designed and constructed to withstand hydrostatic force, the structure can withstand buoyancy force, a sump pump and drain system is in place, and sewer drain lines have backflow prevention valves installed.

STRUCTURE 7. This structure represents multifamily apartment units. Units with reinforced poured concrete walls fared much better than those with nonreinforced concrete block walls as the reinforced concrete walls had more strength to withstand the hydrostatic force. Also, in some units, the saturated soil conditions caused basement floor uplift due to hydrostatic force and cracked the basement slabs because there was no water in the basement to counteract the uplift force. This uplift was transported to the support beam through the column support, which caused the flange of the I-beam to buckle.

Lesson. Tests show that unreinforced poured concrete walls provide more capacity to resist hydrostatic force than do unreinforced concrete block walls of the same thickness. For buildings with block or concrete foundations that have long, unsupported wall spans, offset walls could have been used to support each other and add strength. Failure may still have occurred in such a large flood as the September 1986 storm, but the added strength could have prolonged the walls' ability to sustain themselves against lesser events.

For all units, the basement slab should have been thicker and reinforced. It would then have withstood the hydrostatic force that resulted in damage to the basement floor and to the main I-beam. Structural damage could have been prevented in all units by the use of blow-out plugs. An alternative to prevent building damage due to basement wall or floor failure would have been to fill the basement temporarily with clean water. Another alternative could have been to fill the basement permanently with gravel fill--but only after breaking up the concrete basement floor to prevent hydrostatic force buildup.

CRYSTAL CITY, MINNESOTA

From July 20 to July 24, 1987, thunderstorms dropped 8 to 14 inches of rain, resulting in severe flooding. This flooding lasted 1 to 3 days, which played a role in damaging foundation walls because the surrounding soils became fully saturated. Debris and high-velocity flows were not a factor because much of the flooding was located in backwater areas.

STRUCTURE 8. This two-story, single-family house, which had a full basement foundation of 8-inch-thick non-reinforced concrete blocks, was located 80 feet from Bassett Creek. The house had a 21-foot-wide attached garage, and the entire house was flood proofed with a floodwall.

The flood proofing measure ensured a good foundation for the floodwall and positive cutoff of seepage below the wall. A subsurface drainage system was also constructed. A sump pit with a fully automatic sump pump that had manual override and a high-water alarm was installed. A clay soil mixture fill was placed against the outside of the floodwall to direct drainage away from the wall and reduce underground seepage. For windows outside the floodwall, galvanized window wells were installed.

In the July 1987 flood, the finished basement of the house was inundated by 2 feet of water. This was not caused by overtopping of the floodwall but rather was a result of the sump pump discharge pipe being placed too close to a window well around a window located outside the floodwall. The soil around this window well quickly became saturated and water seeped through the window well. After the owner became aware of the problem, the discharge line was rerouted and flooding subsided, but not before significant financial losses had occurred.

Lesson. An apparently insignificant item of sump pump discharge pipe placement resulted in failure of this system. This structure was also subject to failure due to collapse of the nonreinforced basement walls. Apparently, the sump pump and drain system were large enough in capacity to reduce hydrostatic force on the basement walls to the extent that the nonreinforced walls did not collapse even though saturated soil conditions existed. Flood proofing a structure with a basement is very difficult and is generally not recommended, especially in areas of longer duration flooding where the floodwater is in contact with the structure and no reinforcement exists in the conventional 8 inch-thick concrete block walls.

STRUCTURE 9. This two-story, single-family home was located 70 feet from Bassett Creek. The lower level of the house was a walkout basement. This house was flood proofed with a floodwall.   The floodwall enclosed the entire rear of the house, protecting the walkout basement, and was tied to the house foundation using steel to provide added strength. The footings of the floodwall were reinforced poured concrete and were larger than normally required for a retaining wall of this size to prevent overturning from hydrostatic force. The wall was constructed with 12-inch concrete blocks reinforced both horizontally and vertically. A sump pump and a drain system were installed to drain the enclosed plaza area.

At this site, flooding lasted 36 hours. No major damage occurred. Only a small amount of water accumulated in the basement, entering through two unforeseen weak points in the flood proofing measure. First, an abandoned well pipe in the basement had been improperly sealed. Second, the present owner of the house did not know of the need to turn the sump pump on "automatic" mode.

Lesson. When designing an effective flood proofing system, the designer must always look at small details to anticipate any “weak points” in the system where water can enter. Any “weak point,” no matter how small, can cause system failure.

STRUCTURE 10. This one-story, single-family house, located 470 feet from Bassett Creek, had a full basement with walls of 12-inch nonreinforced concrete blocks. The house was flood proofed with permanent window shields, and earthen fill was placed against the shields and the house foundation. However, no sump pump was installed, and backflow preventors were not included on sewer outlets. Consequently, $2^1/_2$ feet of water collected in the basement and damaged contents and stored materials. Minor cracking was also evident along the front foundation wall.

Lesson. This system failed for two reasons: (1) no sump pump and drain system were installed to evacuate minor seepage and (2) water entered the house through the sewer system, which did not have a back-flow device installed. This resulted in $2^1/_2$ feet of basement flooding. Major structural damage to this structure could have occurred from the hydrostatic force on the nonreinforced foundation walls, which are what caused the observed cracks in the front foundation wall. Obviously, saturation of the soil adjacent to the basement walls did not occur or the nonreinforced walls would have collapsed. The use of 12-inch concrete blocks versus the standard 8-inch concrete blocks aided in preventing major damage. Unless the walls are reinforced to resist the hydrostatic force, the soil is impermeable and floodwater does not come in contact with the foundation walls, or a drain system and a sump pump are installed around the perimeter of the basement with enough capacity to reduce the hydrostatic force, the structure should be wet flood proofed by evacuating all damageable items from the basement and purposely flooding the basement with clear water to prevent further foundation wall collapse due to hydrostatic force. If the walls were reinforced to withstand hydrostatic force due to saturated soil, buoyancy due to hydrostatic force would have to be accounted for.

STRUCTURE 11. This one-story, single-family house, located 160 feet from Bassett Creek had a full basement foundation of 12-inch-thick nonreinforced concrete blocks. The house was flood proofed with a partial 12-inch-thick block floodwall around the rear window and doorway entrance to the basement. The block in the floodwall was reinforced both horizontally and vertically. For windows outside the floodwall, window wells were installed. The plaza area outside of the rear door and behind the floodwall was small and roofed, so no sump pump was installed for internal drainage. Instead, a gravity area drain was used. During the flood of July 1987, the basement of the house was flooded with 2 feet of water because of seepage through the basement walls caused in part by semi-saturated soils. However, no structural damage occurred to the house.

Lesson. A sump pump drain system that can operate with a battery or with generator power should always be installed. As with Structure 10, a nonreinforced block foundation wall forming a basement should not be relied upon to prevent major wall failure in an area where soils can become saturated due to floodwater around or near the structure. Flood proofing basements is never recommended unless the full effects of hydrostatic force, including buoyancy, are designed for.

STRUCTURE 12. This two-story, single-family house, located 40 feet from Bassett Creek had a walkout basement with sliding glass doors. The house was retrofitted with the most expensive flood proofing project in the neighborhood. A floodwall enclosed the entire rear and left sides of the structure.

The floodwall was a T-shaped wall that stood 6.3 feet high. The initial 3-plus feet of the wall was reinforced poured concrete (to withstand hydrostatic force). It was topped by 12-inch-thick reinforced masonry blocks. The wide footings were tied to the wall with reinforcing steel. Extensive landscaping was also incorporated into the design of this flood proofing project to increase the aesthetic appeal of the home. A sump pump was located in the plaza area outside the house but was protected by the floodwall.

During the flood of July 1987, water entered the house; the apparent weak link in the flood proofing system was a window on the non-flood proofed side of the house. The window sill was below the level of the floodwall. Railroad ties were used as a barrier around the window; however, the ties had not been sealed to each other or the foundation wall. Seepage through the ties entered the house through the window sill, with 2 inches of water accumulating in the walkout basement. However, the rear doors were opened to allow floodwater to flow to the outside plaza area. This prevented further floodwater buildup and the sump pump drained the plaza. Other houses in the area had used galvanized window shields. The window well of railroad ties was inferior to the rest of the flood proofing system and was apparently constructed by the homeowner as an afterthought.

Lesson. A very good and probably expensive flood proofing system was not totally successful due to one “weak” spot that apparently seemed insignificant to the homeowner.

MONTGOMERY COUNTY, TEXAS

In May and June of 1989, heavy rainfall resulted in significant flooding in low-lying areas of Montgomery County, Texas. In the Splendors Farms subdivision, several flood proofed structures experienced flooding.

STRUCTURE 13. This house was located less than one-half mile west of Peach Creek and approximately 1 mile north of Waterhole Branch. The wood-frame house had an extended masonry foundation, with the lower area used as a garage and storage area. The primary flood proofing measure used at this house was an earthen ring levee constructed around the structure. The levee was not overtopped; however, an inadequate internal drainage system, in combination with continuous rain for 1 month and seepage through the levee, resulted in high water within the levee and flooding in the garage and storage area.

Lesson. The internal drainage system (1) must be designed in accordance with the event frequency being mitigated by the primary flood proofing measure, which, in this case, was the

levee; (2) must account for the expected levee permeability; and (3) must account for the expected duration of riverine or coastal flooding. The secondary flood proofing measure, which was elevation on extended foundation walls, did not fail.

STRUCTURE 14. This one-story brick house, located approximately 1.3 miles east of Peach Creek and approximately 50 feet from Gully Branch, had a concrete slab-on-grade foundation. A vinyl-coated nylon fabric floodshield was installed as the primary flood proofing measure. During nonflooding conditions, the shield was stored in a metal gutter at grade. The gutter extended over a drain system around the perimeter of the house. The drain led to a sump pump, which was used to remove seepage from the drainage system. During anticipated flooding, the shield was raised and attached onto metal clips in the brick siding. The height of the floodshield in a raised position was 43 inches. Across openings such as doors and windows, the doors and windows provided support . Across the patio, decorative metal railing was used to provide structural support for the shield. However, at these railings, no lateral bracing for the shield was incorporated into the design. To provide lateral support, the owner used a board propped between the rail and wall to transfer some of the hydrostatic load. During the May and June 1989 storms, flood depths rose to 15 inches above grade at the house. Subsequent tests indicated that the railing would have failed at a depth of 43 inches. During these flood events, water did not enter the house. The external air conditioning unit was properly elevated and was not damaged, but an external propane tank was not properly anchored and floated off its base.

Lesson. This flood proofing system worked this time. If the flooding had been higher, the system would have failed due to the lack of adequate support of the floodshield across windows, and at the patio. The openings at windows should have been closed with proper metal or wood closures to provide strength to the fabric floodshield. Across the patio, the railing providing support must be properly supported to the floor by diagonal braces. Some type of solid backing to the floodshield, such as plywood, should have been placed between the railing and the floodshield.

STRUCTURE 15. This one-story brick house, which had a slab-on-grade foundation, was located approximately 80 feet from Gully Branch. The house had a permanently installed system of brick "steps" in front of openings to prevent the flow of water through doorways. During the May flood, the flood level reached 15 inches above grade and overtopped the "steps."

Lesson. Flood proofing measures that can be eventually overtopped can result in damages as if the measure were not in place. Damages could be worse than without the measure if the flood event is of short duration and the flood proofing measure (such as a floodwall or levee that is overtopped) holds the floodwater in the protected area longer. Freeboard, as a "factor of safety" above the level of flood protection desired, should always be considered. The level of flood protection should always be as high as possible for measures that, if overtopped, result in flooding equal to or worse than without protection.

<u>STRUCTURE 16</u>. This one-story, brick house, which had a slab-on-grade foundation, was located one-quarter mile east of Peach Creek. The home was flood proofed with a floodshield (full shield height of 47 inches) similar to the measure installed at Structure 14. However, this measure incorporated two unique design features. First, the floodshield enclosed a large patio area. This added to material and installation costs, increased interior drainage area, and required a larger portion of the shield to be supported by metal railing rather than the building wall. The railing supporting the shield around the patio area included diagonal bracing to the patio floor to support lateral loads. Flood depths reached the top of the shield, but the railing showed no signs of being overstressed. Second, at the front entrance of the house, a free-standing, nonreinforced brick pillar, rather than the more conventional metal railing, was used to support the shield. This pillar, which was 4 feet high and 16 inches wide, had no overlapping joints at successive layers or any ties into the adjacent building walls or porch slab. During the May flood, this pillar failed due to the hydrostatic force, allowing the shield to slump, which created a low point. Floodwaters entered the house and reached depths up to a few inches due to the short duration of the flood crest.

<u>Lesson</u>. This flood proofing measure was very successful except for the one weak point--the nonreinforced pillar. If the duration of the flood crest had been long, total measure failure would have occurred because the "protected" area would have filled with floodwater to the level of the flood crest.

<u>STRUCTURE 17</u>. This one-story, split-level house was elevated on 8-inch-square timber piles spaced 9 feet apart on width and 7 feet apart on length. The front half of the house was elevated 5 feet above grade, and the rear half was elevated 8 feet above grade. During the floods of May and June 1989, flood depths of 27 inches resulted in high-velocity flows that caused localized scour 3 to 6 inches deep around the piles. However, the house suffered no structural or interior damage because the piles were driven to a depth greater than the scour depth.

<u>Lesson</u>. It is important to always keep in mind the potential for erosion and scour when determining the depth of piles, posts, columns, piers, and supporting foundations.

CENTRAL COAST, SOUTH CAROLINA

On September 21 and 22, 1989, Hurricane Hugo, a Category 4 hurricane, battered the coast of South Carolina. The hurricane was followed by rainfall from early morning to early evening on September 25, 1989. During the hurricane, storm surges reached 13 to 20 feet above the mean sea level and winds ranged from 60 to 120 miles per hour. Damage from this hurricane was caused by storm surge flooding, surge-related erosion, wave action, high winds, and rainfall. Warnings had been issued days before the storm hit.

SURFSIDE BEACH, SOUTH CAROLINA

STRUCTURE 18. This one-story, single-family manufactured home, which was located approximately 150 feet from the ocean, was elevated on thirteen $4^1/_2$-inch-diameter steel columns. The lower area was enclosed and used as a living space. The house measured 56 feet by 24 feet, with the longest dimension perpendicular to the ocean. Beneath the house was a concrete slab at grade (pre-storm). This slab was cracked and undermined, but it held in place and acted as a diaphragm and provided rigidity. Approximately 2 to 3 feet of sand, measured horizontally, scoured from under the edge of the slab. Foundation anchorage beneath the slab was provided by steel columns embedded in 28-inch-diameter concrete collars. The embedded depth of the steel columns was unknown. The wall studs were connected to the substructure using hurricane fasteners.

Lesson. This home sustained little structural damage. Even though scour undermined the concrete slab, the columns were embedded deep enough in the ground to prevent damage due to column collapse. A perimeter footing around the concrete slab--constructed to a depth below anticipated scour would have added more safety factor to this structure. The lower living area should not have been enclosed, as enclosures at that elevation allow hydrodynamic force to impinge against the structure. The structure should also have been oriented such that the longest dimension was parallel, not perpendicular, to the ocean. It is surprising that this structure did not fail because the incorrect structure orientation and the enclosed lower area subjected the structure to severe hydrodynamic force and increased localized velocities.

STRUCTURE 19. This one-story, single-family, wood-frame home was elevated on 18 brick columns. There were two rows of seven columns on the south side and two columns at both ends on the north side. The center portion of the lower area was supported on extended foundation walls, which formed a lower area enclosure used as a living space. The brick columns were 16 inches by 16 inches and were connected into a spread footing by two rebars, thus making piers. The spread footing was 36 inches in diameter and 12 inches deep. The brick columns were connected to floor beams with rebar, which was bent at the top and placed through a hole in the beam.

During Hurricane Hugo, the base slab of the lower area enclosure and the oceanside columns were undermined. As a result, the lower area enclosure cracked and part of the foundation collapsed. The primary cause of damage was the lack of proper embedment of the foundation. Wind damage was minimal, as the roof, siding, and windows remained undamaged.

Lesson. Piers should not have been used in an area that can expect high-velocity floodwater and scour. Only piles embedded to depths greater than expected scour should be used. The concrete slab should have been protected from scour by the placement of perimeter footings to depths greater than expected scour. The lower area should not have been used as a living space. It should also not have been enclosed, as this creates higher localized velocities capable of increased scour as water flows around the obstruction.

STRUCTURE 20. This one-story house measured 43 feet by 50 feet, with the broadest dimension perpendicular to the ocean. The house was elevated on thirty 16-inch by 16-inch masonry chimney block columns. Each column was supported on a shallow footing embedded approximately 2 feet, thus forming piers. The columns were connected to the footings by one No. 6 rebar and to the floor beam by bent-over rebar. As a result of the hurricane, seven columns were undermined, pulled from the beam-to-column connection, and collapsed. Other columns were undermined, settled, and separated slightly from the floor beam.

Lesson. The weak points in this flood proofing system were threefold: (1) in a high-velocity area, such as along the ocean where oceanfront property is subject to erosion, only piles made of wood or steel should be used; (2) the piles should be embedded below the ground surface a distance greater than the maximum expected scour; and (3) the narrowest dimension of the structure, not the broadest, should face the ocean.

GARDEN CITY, SOUTH CAROLINA

STRUCTURE 21. This multistory structure faced the ocean and was elevated approximately 7 feet on deeply embedded wood piles. The lower area was enclosed with siding of limited strength. During the hurricane, the piles endured significant debris impact, with no indication of structural distress. None of the pile-to-beam connections failed, but they were not constructed as designed. The piles were notched on top to provide a "seat" for the floor beams. However, the notches were not used. Rather, the beams spanned the top of the piles and were bolted to the beam with galvanized plates. This reduced the overall rigidity of the structure and led to more independent movement of the piles. Thus, the piles were less able to act as a unit and resist lateral wave impact forces.

Damage at this house was limited to the pool and patio and to the siding used to enclose the lower area. The siding had limited strength and, as such, it performed as a breakaway wall, shearing off at the main support beam. It is interesting to note that this house suffered no structural damage while the neighboring structure, which had a slab-on-grade foundation, was subject to similar forces and was destroyed.

Lesson. In this case, the piles were made of wood (which is acceptable) and were embedded below the ground surface far enough so scour was not a problem and the piles could resist the bending moment created by the hurricane force wind against the multistory building. Another key to the success of this flood proofing system was the breakaway siding enclosing the lower area of the building. The breakaway siding allowed water to flow relatively unimpeded (except for accumulated debris) under the structure. This reduced or eliminated a major problem--scour due to water having increased localized velocity as it passed around a larger obstruction created by nonbreakable siding.

The neighboring house with slab-on-grade construction was probably destroyed for two reasons: (1) the slab-on-grade house had to endure the hydrodynamic force of water directly impinging against the structure and (2) localized floodwater velocities were increased due to the obstruction to floodflows of the structure at grade. These increased velocities would have produced more localized scour, undermining the slab-on-grade foundation.

STRUCTURE 22. This two-story, single-family house was elevated on eighteen 10-inch-diameter wood piles embedded approximately 10 feet. Cross bracing and knee bracing were parallel to flow, with no bracing perpendicular to flow. This provided less area for hydrodynamic and debris impact loads. The main floor support beams were also parallel to flow to minimize the effects of wave impact. The beams rested in notches at the tops of the piles and were connected with $2^{3}/_{4}$-inch bolts. The uplift connections between the floor joists and the support beams were galvanized metal hurricane fasteners. There was a 4-inch-thick concrete parking slab at grade beneath the piles. During the storm, this slab was undermined on the ocean side and partially collapsed. However, the collapse did not cause any structural problems. Water damage from storm surge and wave forces was limited primarily to an oceanside deck, the front entrance stairway, and the concrete parking slab. There was minimal wind damage because the owner boarded up the oceanside windows, roof eaves were kept to a minimum, and hurricane fasteners were used throughout the structure to form a continuous connection from roof rafter to foundation.

Lesson. This structure's flood proofing system proved to be very sound. Damage to the concrete parking slab could have been eliminated with perimeter footings embedded below the expected scour depth.

PAWLEY'S ISLAND, SOUTH CAROLINA

STRUCTURE 23. This one-story, single-family home located several hundred feet from the ocean was elevated on square timber columns. The columns were connected to 4-foot by 4-foot by 3-foot concrete footings that were embedded just below the pre-storm beach level, thus forming piers. The massive size of the footings kept the structure upright, but the shallow embedment depth caused the columns to lean landward due to hydrodynamic force against the structure and loss of supporting soil around the footings due to scour.

Lesson. This flood proofing system would have been successful if not for the inadequate embedment depth of the pier footings. The cost to embed these footings deeper to be below scour depth and to enable the structure to better resist the hydrodynamic force would have been relatively insignificant at the time of initial construction. The best alternative, however, would have been piles driven deep enough to be below scour depth and to be able to resist the bending moment due to the hurricane force wind impinging upon the elevated structure.

<u>STRUCTURE 24</u>. This two-story, single-family structure was elevated on square timber posts connected to concrete footings. The footings were connected by a poured concrete grade beam. Steel plates in the footings were bolted to the posts. Several bolts and fasteners showed signs of significant corrosion and would not be easy to replace. The structure weathered the storm in spite of poor design of the shallow foundation.

<u>Lesson</u>. This flood proofing system was apparently adequate this time. However, the severely corroded metal fasteners may not provide the needed strength the next time this structure is tested. This shows that these types of fasteners should not be used where corrosion can occur. Proper maintenance may have prevented the corrosion. The problem here is that many homeowners will not provide the maintenance. A solution to the corrosion problem may be to replace the existing connectors with stainless steel or galvanized connectors and to use caulk to seal out salt water. The shallow foundation system should not be used in hurricane areas. See the “Lesson” for Structure 23.

<u>STRUCTURE 25</u>. This three-story condominium complex was elevated on concrete piles. All but one pile withstood the storm. The one pile that was destroyed was attached to a wooden bulkhead that acted as the "ultimate" nonbreakaway wall. This bulkhead was constructed directly in the front of the structure, facing the ocean, and did not fail, thus transferring the full wave force directly to the pile and causing it to fail. The base slab was undermined and collapsed.

<u>Lesson</u>. This flood proofing system sustained damage because of one basic mistake--constructing a nonbreakaway wall that (1) transferred hydrodynamic force to the supporting pile and (2) created higher localized velocities that scoured the soil beneath the base slab. The base slab could have been protected with perimeter footings embedded to below scour depth.

DEBIDUE BEACH, SOUTH CAROLINA

<u>STRUCTURE 26</u>. This two-story, single-family oceanfront home was constructed partially on piles and partially slab-on-grade. The center portion of the lower area was wood-frame construction built up from the base slab, and the left and right sides were elevated above the inhabited lower area enclosure. The slab and piles were undermined, causing the center portion to list toward the ocean and the north side to completely collapse. The north side disconnected at the adjoining roof lines without structurally damaging the center portion of the roof.

<u>Lesson</u>. Three basic mistakes occurred with this system: (1) the slab-on-grade construction allowed hydrodynamic force to directly impinge on the structure and localized floodwater velocities to increase, creating increased scour potential; (2) the piles were not

embedded deep enough below grade; and (3) the concrete slab-on-grade did not have perimeter footings to prevent scour from occurring beneath the slab.

<u>STRUCTURE 27</u>. This one-story, single-family home was moderately elevated by concrete columns embedded only a couple of feet into the sand. The columns rested on shallow footings, thus forming piers. They were connected to the superstructure with bolts and fasteners attached to a wood post extending from the main support beam.

The storm's waves eroded the supporting sand, causing the oceanside portion of the house to lean. The differential settlement caused the house to crack from the floor beam to the roof line. The storm eroded sand from beneath the shallow footings, causing them to lose bearing capacity and leaving some of the piers in mid-air. The dead weight of the concrete piers caused the bolt connection at the wood post to fail. Also, the concrete pad under part of the building was undermined and broke off in sections.

<u>Lesson</u>. Two critical mistakes were made in the system design: (1) piers should not have been used where high velocities occur and (2) the embedment of the footings below grade was not below the scour depth. Piles embedded below the scour depth would have made this flood proofing effort successful.

CHARLESTON COUNTY, SOUTH CAROLINA

<u>STRUCTURE 28</u>. This two-story, wood-frame house in Romain Retreat was elevated on eighteen 9-foot-high masonry columns with six additional columns at grade supporting the rear porch. The masonry columns were constructed of 8-inch by 12-inch by 12-inch masonry chimney units filled with grout and reinforced with four No. 4 rebars, with the overlap of spliced bars being only 6 inches. The columns were constructed over a concrete base slab, with rebars tying the columns to the slab, thus forming piers. The lower area was enclosed by brick walls that were not tied to the slab or elevated floor.

Most of the 24 piers collapsed from the storm. The connective fasteners, which were $2^1/_4$-inch-wide by $^1/_8$-inch thick galvanized steel, failed under surge and wind forces. Each pier contained two fasteners, which were embedded in 12 inches of grout fill and connected to each side of the timber floor beams by two $^1/_2$-inch diameter bolts. The exposed portion of the fasteners were severely corroded. The failure occurred at the exposed (corroded) portion of the fasteners rather than at the bolts due to the loss of cross sectional area.

<u>Lesson</u>. The failure of the fasteners due to corrosion contributed to the overall system failure. Proper maintenance and the use of stainless steel or galvanized connectors protected from salt water could have prevented this. Thicker connectors would also have been helpful. The major system failure, however, was pier failure. This occurred because of four reasons: (1) inadequate embedment

depth below grade of the pier footings, allowing scour to occur below the footings; (2) inadequate reinforcing steel overlap length at splices that did not give the column the strength to resist wind forces against the two-story house; (3) perhaps inadequate column size; and (4) the lower area enclosure made of brick that did not break away and caused larger hydrodynamic force on the adjacent columns and increased localized velocities, causing increased scour. Piles should always be used in coastal areas that are subject to erosion. Piers should never be used unless the footings are protected from scour.

STRUCTURE 29. This house was similar in design to its neighboring house in Romain Retreat (Structure 28) in that a pier design was used, but this structure did not fail.

Lesson. There were several differences between this structure and Structure 28, which failed. First, larger concrete masonry units (measuring 8 inches by 16 inches by 16 inches) were used in constructing the columns. Second, heavier galvanized metal fasteners (measuring $2^1/_4$ inches by $^1/_4$ inch) were used. These larger fasteners lessened the effects of corrosion. Third, breakaway wood lattice walls rather than brick walls were used to enclose the lower area, decreasing the effect of hydrodynamic force with no increase in local velocities and hence higher scour levels. Fourth, the pier embedment depth may have been greater. This pier-supported structure survived this test. However, piers are never recommended in a coastal area subject to scour potential.

STRUCTURE 30. This one-story, single-family home located in Isle of Palms was located behind a well-vegetated substantial dune system. The house was elevated on 7-foot-high masonry piers constructed from 12-inch mortared blocks. The storm surged 5 feet below the structure. The well-established lawn and dune helped prevent the scour of the piers.

Lesson. This structure probably would have failed due to scour beneath the piers if it had not been for the dune system.

STRUCTURE 31. This single-family house in Isle of Palms was located approximately 150 feet from the ocean. The house, which measures 40 feet by 50 feet, with the broadest dimension parallel to flood and wind forces, was elevated on 10-inch-diameter wood piles 9 feet above grade. The piles were cross braced with 2-inch by 12-inch wood both parallel and perpendicular to flow. Approximately 25 percent of the cross bracing in the outer bays perpendicular to flow was damaged due to surge forces and debris impact.

The house also had an at-grade deck of wood planks beneath the structure. Uplift from waves caused some of the deck planks to be removed from the deck framing. However, the wood deck was better than a concrete slab because erosion did not cause as much damage and repair costs were less. In addition, the access staircase to the house was enclosed from the handrail to the stair, adding surface area for wave and impact force which led to the failure of the stairs.

Lesson. Minimizing the amount of obstruction beneath the house to hydrodynamic force results in less structure damage.

STRUCTURE 32. This two-story, single-family home located approximately 150 feet from the ocean in Isle of Palms, was elevated on forty-eight 10-inch-diameter wood piles. The house was 48 feet by 42 feet, with the broadest dimension perpendicular to flow. Tensile bracing of the piles (consisting of ½-inch braided steel cable) was placed both parallel and perpendicular to flow. The house support beam sat in a notch on the pile and was bolted with $^3/_4$-inch-diameter bolts. Although a section of roof was damaged, the house was not significantly damaged.

Lesson. This flood proofing system worked because of two basic reasons. One, piles, rather than piers, were used in an area subject to coastal-related erosion. Two, the lower area was not obstructed by enclosed areas. It should be noted that this structure was cross braced with steel cable (minimal obstructive effect) and was not damaged like Structure 31, which used wood bracing (larger obstructive effect).

STRUCTURE 33. This two-story, single-family house in Isle of Palms was an example of extraordinary effort in coastal construction. The house was elevated by wooden posts above the flood event that occurred, and the lower area was enclosed with breakaway walls that were partially cut 3 feet below the house to create a weak point for clean shear off. Most of the breakaway wall did fail at the cut.

For this event, the utilities and duct work under the structure were not damaged by turbulence from water passing beneath the structure because they were sufficiently elevated. All duct work was encapsulated with plywood to prevent its being pulled off by water. When compared to the damage that occurred to utilities at nearby homes, this extra effort proved to be cost effective.

A concrete slab used for parking and storage beneath the structure was damaged due to erosion beneath the slab. The main house structure was strengthened by wooden posts from below grade to the roof. There was one joint, at the first floor, where adjoining posts were bolted together. Railing was placed between posts at each floor to further strengthen the structure. Each railing was screwed to the post with stainless steel screws, and each joint was caulked to seal out salt water mist and to prevent corrosion. Roof construction consisted of $^3/_4$-inch tongue-and-groove plywood instead of the normal $^1/_2$-inch thick plywood. Thus, the roof was able to act as structural support for the framing. Before installing wood plank siding on the house, the builder predrilled each hole to avoid splitting the woodframe boards which could provide a weak point for wind damage.

The roof covering also survived well, as additional precautionary techniques were implemented during construction. Metal flashing was placed under the shingles at cap lines, the roof overhang was almost flush to the walls, and the ends of the shingles were sealed to the roof.

<u>Lesson</u>. Extra care and expense taken when designing and constructing a flood proofing system pay dividends when the system is tested. One item that was overlooked in the system was perimeter footings around the concrete slab to prevent scour under the slab. Another item was piles, which should have been used in lieu of posts in a coastal area subject to erosion.

<u>STRUCTURE 34</u>. This two-story, single-family, wood-frame house in Isle of Palms was located approximately 75 feet from the ocean. The house was elevated on piles at a level to accommodate the storm event without storm surge. Therefore, the floor system was inundated approximately 1 to 2 feet by the storm surge. Incoming waves caught the bottom of the floor joist and impacted the underside of the structure.

The house suffered severe damage. The entire oceanside wall and approximately 30 percent of the street wall were removed. The walls were ½-inch plywood sheathing coated with a stucco face. The sheathing and stucco cracked and broke at the damaged areas.

The floor joists on the street-side perimeter of the building failed. They were nailed at one end and bolted at the other. As the nails were pulled out, the beam acted as a lever to pry the bolted connection. The oceanside joists were also ripped out, but it could not be determined how they were connected to the supports. The floor joists were perpendicular to flow. Thus, they were ripped out by the flood force, although the floor itself remained in place by resting on the piles.

<u>Lesson</u>. The flood proofing system simply did not elevate the structure high enough to be above the storm surge. Less damage would have occurred to the house even at its existing elevation if the floor joists would have been oriented parallel to the storm surge.

<u>STRUCTURE 35</u>. This two-story, single-family home (also in Isle of Palms) was located approximately 30 feet from the ocean behind a riprapped embankment and was elevated 7 feet above grade on 36 piles that were 10 inches in diameter. The lower area was enclosed. The storm surge was higher than the lowest elevated floor. The ocean side wall and a section of floor were removed by the storm surge, and the main support beam failed. There was a masonry cinder wall extending from the slab to the elevated floor at the ocean side of the lower area enclosure. The connection between this wall beam may have been the cause of failure of the main support beam. In addition, much of the riprap became water-borne projectiles, which tore through the lower area. Also, the piles were cross braced perpendicular to flow, and the first row was destroyed.

<u>Lesson</u>. This flood proofing system had three basic problems. First, the riprap placement was a mistake since the riprap was forced into the structure by the storm surge. Second, the structure was not elevated high enough for this particular event. Third, the masonry wall enclosing the lower area transferred hydrodynamic force to the piles, adding to failure. The cross bracing between the piles perpendicular to floodflows probably accumulated debris, which, when combined with the impact of the storm surge driven riprap, caused pile failure.

STRUCTURE 36. This one-story, single-family home was elevated on wood piles. The wave crest just reached the underside of the structure, ripping away plywood sheathing on the frame and causing severe damage. The house shifted 2 to 4 inches landward. Several piles became misaligned. In the north wing, the entire wall and floor systems were destroyed because the principal support beam for the north wing was located perpendicular to flow.

Lesson. This structure may have not been damaged if the flood proofing system had elevated it above the storm surge. Also, alignment of the floor support beams parallel to the storm surge would have helped to reduce damage.

STRUCTURE 37. This two-story, single-family home in Isle of Palms was elevated 7.5 feet above grade on thirty 13-inch by 13-inch masonry block columns filled with reinforced concrete. The columns were supported by wooden piles embedded 12 to 18 feet below grade. The pile-to-column connection was provided by a concrete slab poured as a pile cap. The lower area was enclosed. Both the street and ocean sides of the lower area were enclosed with a breakaway lattice, which had 50 percent open area. During the storm, the lattice did break away as intended. The side walls of the lower area enclosure consisted of concrete blocks and windows. The column-to-beam connections were not properly galvanized. Overall, this house suffered very little damage, and the flood proofing system performed well.

Lesson. This flood proofing system elevated the structure sufficiently. The column support piles were embedded well below scour depth. The depth of the embedded piles provided strength from wind loading. Three additional measures that could have been included in the flood proofing system are (1) placing perimeter footings around the slab to prevent any scour under the slab, (2) building all walls of the lower area enclosure with breakaway materials, and (3) using connectors that are either stainless steel or galvanized metal and inspecting and maintaining them annually.

STRUCTURE 38. This one-story, single-family home in Isle of Palms was both elevated on concrete block columns and protected by a fairly large dune. The lower area was fully enclosed and used as a two-bedroom apartment. The lower area was destroyed, but no structural problems occurred to the elevated structure.

Lesson. The large dune probably saved this structure from complete damage due to storm surge and hydrodynamic force. The obvious major mistake with this structure was completely enclosing the lower area and using it as developed living space. This major obstruction, if not for the large dune, would have created such localized high velocities that scour plus the large hydrodynamic force transferred to the columns by the enclosure of the lower area may have destroyed the entire structure.

STRUCTURE 39. This one-story, wood-frame house in Isle of Palms was elevated on forty-two 8-inch by 8-inch wood posts. The posts were strapped and bolted to a concrete grade beam that

was embedded more than 12 feet deep. The central portion of the house was a 60-foot by 24-foot rectangle. Wings were attached to both ends, extending the width of the central portion of the house.

The elevating posts had bracing both parallel and perpendicular to flow. The floor beams were perpendicular to flow and were bolted and fastened to the posts. The construction of this house included extensive use of hurricane fasteners.

Wind forces dislocated and destroyed the southern wing, which had a relatively large surface area for the wind to act on due to the height of the inner wall and the distance the wall extended from the center of the house. The posts supporting the southern wing were pulled from their connections, but the fasteners did not fail. Rather, the posts cracked and pulled away from the connections. There was no apparent damage to the northern wing or to the center portion of the house.

Lesson. The flood proofing system for the structure was successful, but the wind proofing system was not. Larger connector attachment brackets would have prevented the detachment of the connectors from the wood posts.

STRUCTURE 40. This one-story, single-family home in the Isle of Palms was constructed of reinforced concrete and was elevated on 18-inch-square reinforced concrete columns which extended to the roof line. The columns were embedded deep enough to stabilize the structure, but the embedment depth was unknown. The floor system was not the typical wood frame but rather was 24-inch precast, prestressed double concrete tees locked together parallel to the shoreline. The beam-to-foundation connection utilized a bearing pad. A 9-foot by 16-foot portion of the lower area was enclosed with masonry block walls. These walls were not instrumental in providing structural support to the building and suffered no damage. This house withstood tremendous forces as evidenced by the neighboring restaurant that was completely destroyed.

Lesson. In "normal" flood proofing system construction, the nonbreakaway walls around the lower enclosed area would have created problems due to scour and increased hydrodynamic loading on the columns. However, in this case, the structure and the flood proofing system were integral to one another to such an "overdesigned" extent by "normal standards" that the presence of the nonbreakaway walls had no effect on this structure.

STRUCTURE 41. This one-story, single-family home in Isle of Palms was located only 20 feet from the ocean. The house was elevated on twenty 8-inch-square wood piles. The embedment depth was unknown but seemed to be adequate since the piles remained embedded even after 2 feet of sand was eroded by the storm. The piles had wood cross bracing perpendicular and parallel to flow. The lower area was enclosed with lattice breakaway walls that had 80 percent open area. A concrete slab at grade under the left side of the house was used for parking. This slab was undermined on the ocean side and collapsed after approximately 2 feet of sand was removed by the storm.

Hurricane fasteners were used extensively throughout the structure. The street and ocean side staircases also had hurricane fasteners and did not experience damage.

Lesson. The only apparent problem with this system was the lack of perimeter footings around the concrete slab to prevent scour. The wood cross bracing perpendicular to the storm surge should have been avoided by using cables if bracing was necessary in that direction.

STRUCTURE 42. This two-story, single-family home in the Isle of Palms, which was located approximately 50 feet from the ocean, was subject to severe on- and off-shore winds. The house was elevated on twenty 12-inch-diameter wood piles. Floor beams ran parallel to the flow and connected to the foundation with $^{3}/_{4}$-inch-diameter bolts with a single notch in each pile. The floor joists were toe-nailed to the floor beams. Hurricane fasteners were used on the other connections.

Surge forces removed approximately 65 percent of the horizontal wood plank wall on the ocean side. However, the most intense damage was the loss of the roof. The low-pitched gable with gable ends faced the direction of wind. The roof overhang was less than 1 foot. A window in the hip of the roof may have let wind in, which then caused the loss of the entire roof. Without the roof to act as a support for the walls, the walls fell outward. Hurricane fasteners had been used, but most of the house was infested with wood worms. The resulting poor wood quality resulted in the failure of the wall-to-roof connections.

Lesson. From a flood proofing system viewpoint, this system was not elevated high enough to be above the storm surge.

ST. LOUIS, MISSOURI, AND VICINITY

During the spring and summer of 1993, extremely heavy rainfall over a prolonged time period occurred throughout the Upper Mississippi River basin. This rainfall on top of the wet soil conditions from the previous year created record flooding at many locations on the Upper Mississippi River, the Missouri River, and their tributaries.

CRYSTAL CITY, MISSOURI

STRUCTURE 43. This site consisted of three industrial/commercial buildings that were flood proofed by a partial ring levee tied into high ground at each end. The three buildings were slab-on-grade construction with exterior walls of concrete block. They were located 500 feet from the Mississippi River but were not in direct line of floodflows. Floodwater was against the levee for several days. The area soil was a silty clay. Flood warning time was several days. Flood debris at the site was average. The levee was a maximum of about 8 feet in height with a 6-foot top width. A majority of the levee was constructed with sideslopes at least as flat as 1 vertical to 2 horizontal. However, a portion was constructed with sideslopes of 1 vertical to 1 horizontal due to area constraints. The levee

was vegetated with grass. The levee interior was drained by gravity. The buildings each contained a sump pump. A flood fight was waged by placing sandbags on top of the levee. Since this was a partial ring levee, an escape route to high ground was available for those placing sandbags. The flood proofing system failed because of weakened levee conditions due to the narrow levee with sideslopes of 1 vertical to 1 horizontal, the prolonged flood duration, and overtopping at this location, which resulted in levee breaching.

Lesson. In this case, all parts of the flood proofing system functioned as intended except that the levee was overtopped, leading to levee breaching. Obviously, the levee should have been higher for this event. The levee failed where the sideslopes were 1 vertical to 1 horizontal. Levee breaching may not have occurred if flatter sideslopes (1 vertical to 3 horizontal or flatter) had been used. Sideslopes of 1 vertical to 1 horizontal are without question too steep for reliable levee stability. Without levee breaching, a successful flood fight may have been possible. This flood proofing system had a definite weak point -- that portion of the levee with the 1 vertical to 1 horizontal sideslopes. If not enough area was present for a levee with flatter sideslopes, a floodwall should have been built in that location.

Looking at the portion of the partial ring levee with flatter sideslopes. Note the opening that was closed with a closure structure that was successful. Note the sandbag flood fight on top of the levee.

Looking at the portion of the partial ring levee with steep sideslopes that resulted in complete failure due to breaching.

HERCULANEUM, MISSOURI

STRUCTURE 44. This site was about 300 feet from a backwater area connected to the Mississippi River. Flood duration and warning time were several days. The flood proofing system at this location consisted of a floodwall tied to high ground at each end. The system protected several mobile homes, a laundromat, and a store. At the highest point, the floodwall was 6 feet high. It was supported at intervals by means of concrete braces located on the “wet” side of the floodwall. The floodwall was overtopped by 3 feet, the mobile homes were destroyed, and the two permanent buildings were severely damaged.

Lesson. This system apparently worked well until it was overtopped. Floodwall bracing, if placed on the "dry" side of the wall, would provide more reliable support in a compression rather than tension mode. In regard to the wall being overtopped, a 9-foot-high wall (to eliminate overtopping in this event) probably would have been more expensive than relocating the mobile homes and two permanent buildings. Relocation out of flood-prone areas is the ultimate in flood proofing. Conducting a flood fight by raising the wall with temporary "flashboards" made of supported plywood may have been possible, although a 3-foot extension on a 6-foot wall would probably have reached the upper limits of reliability.

Looking at the floodwall and also the building on the "protected" side. Note the bracing on the "wet" side of the floodwall.

BARNHART, MISSOURI

STRUCTURES 45, 46. These structures are both one-story, single-family houses. Structure 45 was protected by a floodwall with closures. Structure 46 was protected by elevation on extended foundation walls. Both were located in low-velocity flood areas away from the Mississippi River. Both flood proofing systems were overtopped by several feet. They are presented here as typical examples of flood proofing measures that work well when designed to protect against a particular flood. The flooding in 1993 was so record breaking that little can be learned from the failures of these systems other than the structures should have been protected to a higher level or relocated.

Lesson. Flood proofing systems that rely on elevation will probably have the protection level exceeded at some time in the future.

ST. LOUIS, MISSOURI

STRUCTURE 47. This was a commercial/government building measuring 75 feet by 1,000 feet. It was a slab-on-grade structure with the 1,000-foot side parallel to the floodflow. The building was about 50 feet from the River Des Peres. The structure was protected by a floodwall built in the late 1970's. The wall was generally 5 to 6 feet in height, with a maximum of 10 feet. The floodwall was between high ground and a railroad embankment serving as a levee. It protected against floods prior to 1993. During the 1993 flood, the floodwall was raised 4 feet with plywood extensions diagonally braced to the ground or laterally braced to the building with 2-inch boards. The system still overtopped, causing catastrophic flooding to the building and its contents. Floodwater velocity was not a problem.

Lesson. All flood proofing systems relying on barriers of some type to hold back floodwater at an elevation higher than the structures' first floors are subject to massive damage from overtopping. In this case, ultimate flood protection was not achieved, even with barrier construction and a valiant flood fight. In addition, a basic problem with wall flood proofing systems is the potential physical limit of raising the protection level during a flood fight. In this case, further reliable extension above the 4-foot level would have been increasingly difficult in contrast to a levee flood proofing system that, because of its wider base, would make a flood fight to greater heights much more feasible. A flood proofing measure to consider in commercial/industrial buildings is wet flood proofing if the damageable property can be permanently elevated or if a system of quick disconnects and evacuation can be employed.

ST. GENEVIEVE, MISSOURI

STRUCTURE 48. This was a commercial structure having 92,000 square feet of first floor area. It was a slab-on-grade structure with block/brick walls located about 1.5 miles from the Mississippi River. The flood proofing measure consisted of a levee about 6 feet high with 1 vertical to 3 horizontal sideslopes. The levee was located from zero to 6 feet from the structure. The levee tied to high ground at each end. Interior drainage was provided by two 10-inch pumps and gravity drains. Two additional pumps were installed during the 1993 flood. This flood proofing system was successful but only after a serious flood fight. The original levee, which was built with little engineering analysis, was composed of "lime screenings" (2-inch or less rock) with a plastic cover held in place with sandbags on the river side of the levee. During the flood fight, the levee was raised 6.5 feet with more "lime screenings" covered with plastic. An additional 3-foot raise was achieved with sandbags. This barrier, plus the interior drainage pumps, kept the structure flood free.

Lesson. This flood proofing system was successful because it could be raised to accommodate the 1993 flood levels. The raise was possible (9.5 feet on top of an original 6-foot-high levee) because the original flood proofing system base (the levee) was broad enough to satisfactorily accommodate a reliable raise to such an extent. In addition, the structure owners added more pumps

and provided the flood monitoring to give more reliance to their system. If this had been a "ring" levee, onsite flood monitoring would not have been advisable due to the inability to escape if the flood proofing system failed.

<u>STRUCTURE 49</u>. This structure was a commercial building measuring 60 feet by 100 feet with a slab-on-grade foundation. The exterior walls were concrete blocks. The flood source was about 1.5 miles away. The building was wet flood proofed to a depth of 10 feet. The 1993 flood was 12 feet in depth at this location--flooding utilities, equipment, and supplies that had been permanently elevated or stored on raised platforms. Damage to equipment, inventory, utilities, and the finished building interior was sustained.

<u>Lesson.</u> This building and its contents sustained damage due to 2 feet of flooding with failure of this system versus 12 feet of flooding if a system of barriers had been used and failed. Because of this, a wet flood proofing system shows system benefits even with failure due to inadequate elevation.

<u>STRUCTURE 50</u>. This one-story commercial building measured 60 feet by 60 feet with a slab-on-grade foundation and brick exterior walls. It was about 1.5 miles from the flood source. The flood proofing measure used was elevation on fill that extended up above grade about 12 feet. The 1993 flood was 10 feet above grade at the site.

<u>Lesson</u>. This system was successful because the building owner at the time of construction went to the extra expense of flood proofing to a higher level than most people do. It paid off in 1993. From strictly a flood damage viewpoint, this system was surpassed in effectiveness by only one other type of flood proofing--relocation out of the flood plain.

ST. LOUIS, MISSOURI, VICINITY

<u>STRUCTURE 51</u>. This structure represented the numerous single-family homes and small commercial buildings that employed the flood proofing measures of elevation on piles, posts (columns), piers, and extended foundations walls. These homes were not in high-velocity areas.

<u>Lesson</u>. The only factor that separated a successful system from a failed system was whether or not the home was elevated so the first floor elevation was higher than the flood elevation. The type of support (posts (columns), piles, piers, or extended foundation walls) and the number, size, and composition of the supports (steel, wood, or concrete block) did not matter relative to the success of the flood proofing system. Bracing the supports also was not a factor relative to low-velocity floodwater. Bracing would be a factor, as would support size, type, and number and also the elevation measure used, for those elevated structures that could be affected by wind and hydrodynamic force. The real lesson is to always elevate as high as possible without becoming so high that mitigating wind and/or seismic forces becomes so costly compared to mitigating flood forces only that relocation becomes most feasible.

Looking at a typical structure elevated on extended foundation walls. Flood depth was about one foot above the main (elevated) floor. Note the elevated utilities on the outside wall.

Looking at a typical structure elevated on masonry columns with bracing. The structure is nontypical because it was the only elevated structure viewed that was above the flood.

Looking at a typical structure elevated on masonry columns that had water above the main (elevated) floor.

NUTWOOD, ILLINOIS

STRUCTURES 52, 53, 54, 55. These structures were located in a row parallel to and about 200 feet from a levee that provided protection from the Illinois River. The levee was several feet high and was not considered a flood proofing system because it protected a very large area, not a single structure or single group of structures. The structures were single-family homes, with the first floors flood proofed by elevation on extended foundation walls. Floodwater velocity through the area was very high as a result of the adjacent levee overtopping. A levee breach in the area did not occur. The floodwater elevation was lower than the first floor elevations of the four structures. Scour was not apparent to any great degree in the area.

Lesson. In each of the four cases, the flood proofing system provided sufficient elevation for the first floor. The problem was the extended foundation walls that were constructed of concrete block completely enclosing the lower area with the exception of doors and windows. This enclosure created an obstruction to the high-velocity floodwater, thereby subjecting the walls to large hydrodynamic force. Two of the structures totally collapsed due to complete failure of the extended wall support system. No steel reinforcement or grouting in the walls was apparent. The other two structures were standing, but one side of the extended concrete block wall supporting the first floor collapsed on each structure. Examination of the collapsed walls on these two structures showed some vertical reinforcement of the wall with rebar and grout. No lateral reinforcement was observed. In all

four structures, the extended concrete block wall to support the structure should not have been used in an area close to a major river where high velocity during floodflows could occur. Supports such as columns, posts, or piles embedded sufficiently below grade should have been used, with piles being the preferred choice. Any enclosure of the lower area should have been of minimal strength to easily break under hyrdodynamic force.

Looking at Structures 52 and 53.

Looking at Structures 54 and 55.

HERMAN, MISSOURI

STRUCTURE 56. This was a large industrial building protected from backwater from the Missouri River by a floodwall. The floodwall was tied to high ground on each end, although it almost surrounded the building. Both the building and the original floodwall were old. The footings of the original wall were unknown. A portion of the original wall was still in place. The minimum distance from the wall to the building was 4 feet. The floodwall was raised on a permanent basis two times. The original wall height varied from zero to 4 feet. Each upward extension was 2 feet. Rebar tied the top 2-foot extension to the middle 2-foot extension. It was unknown prior to failure if the middle 2-foot extension was tied to the original wall with rebar. Interior drainage was provided by one permanent pump and temporary pumps as needed during flood events and by gravity through 4-inch drainage holes in the wall bottom during nonflood periods. The drainage holes were plugged with inflatable rubber "balloons" during flood events. The total floodwall length was about 880 feet. Closures in the wall consisted of boards placed in a slot in the floodwall and made watertight with asphalt roofing material, jute packing, and plastic sheeting.

Lesson. About 150 feet of the wall collapsed at the seam between the original wall and the first 2-foot extension. Of the 150-foot section that failed, a 90-foot section had foundation failure. Both failures occurred because (1) the original wall footing was not designed for extensions doubling the original wall height and (2) the assumption that rebar tied the first extension to the original wall was false. Upon wall failure and due in part to the close proximity of the wall to the building, the building roof subsequently failed. After the flood, the building was being abandoned and the industry was relocating to a flood-free site.

Looking at the floodwall. Note the closures at left and far right, the original floodwall, and the two additions. The failed portion is between the building and the trees in the background.

Looking at the original floodwall. Note the foundation failure resulting in wall misalignment. Also, note the absence of rebars on the original floodwall.

Looking at the collapsed floodwall additions. Note these two additions are still tied together with rebar.

CENTRAL IOWA

Central Iowa in the summer of 1993 was similar to most parts of the Upper Midwest in that wet antecedent moisture conditions existed as a result of abnormally wet conditions beginning in the fall of 1992 and continuing through the following season. In the Ames, Iowa, area, the climax in terms of flood stages to these wet conditions occurred on July 9, 1993, when Squaw Creek reached a record flood elevation. The flood discharge was in excess of 21,000 cubic feet per second (c.f.s.), as compared to the published FIS 100-year discharge of 8800 c.f.s.

AMES, IOWA

Structures 57 and 58 had been built since approximately 1970. At the time of construction, they were both flood proofed to protect against a 100-year flood event. The 1993 event was so much larger than a 100-year event that the flood proofing systems were simply exceeded. However, some lessons can still be learned from these two structures.

<u>STRUCTURE 57</u>. This large structure had interior floors lower than the 100-year flood elevation. The major path of floodwater entry was at the top of an east-side ramp down to the lower level. The top of this ramp failed due to underseepage and overtopping. Another point of floodwater entry was the pedestrian doors, which were made of glass in metal frames.

<u>Lesson</u>. Ultimate failure occurred because of the record flood elevation, which exceeded the design elevation. However, prior to that elevation being reached, problems were occurring due to the lack of floodshields at the pedestrian door and at the top of the ramp. Underseepage cutoff walls were needed at the ramp to prevent the occurrence of the underseepage. With flood proofing to accommodate the record 1993 flood, increased hydrostatic force would require the sealing of all underground conduits entering the building and the placement of manual shutoff valves on all sanitary sewer lines. Interior sump pumps were operated by an emergency generator, which operated on city water for cooling. A backup closed cooling system is needed to ensure operation during floods. Operation of the pumping system is critical to relieving seepage due to hydrostatic force.

<u>STRUCTURE 58</u>. This large structure was located in close proximity to Structure 57. The building was flood proofed by elevation in excess of 1.5 feet above the 100-year flood elevation. Floodwater entry to the building was primarily through doors and windows.

<u>Lesson</u>. The existing flood proofing system was adequate for the design flood but was inadequate for the 1993 flood. Floodshields need to be installed at all openings. All conduit entrances to the building need to be sealed and manual shutoff valves installed in sanitary sewer lines as a precaution against water entry due to increased hydrostatic pressure for a flood proofing system design to accommodate the 1993 flood elevation.

SOUTHEASTERN TEXAS

The flooding in the fall of 1994 in the Houston, Texas area, resulted from extremely heavy rainfall in the San Jacinto River basin. Flooding in the eastern Houston metropolitan area was characterized by large depths combined with areas of extreme high velocity.

HOUSTON, TEXAS

STRUCTURE 59. This single-family home was constructed in 1983 on 10-inch by 10-inch wooden posts spaced about 10 feet apart. The posts varied in embedment depth below grade from 4 feet to 8 feet with no concrete in the post hole. The building's first floor was elevated about 10 feet above grade. The building was located about 30 feet from the bank of the San Jacinto River. The flood depth was about 4 feet around the structure. A concrete slab-on-grade was in place beneath the structure. A closed-in utility room was in place in the lower area between the slab-on-grade and the first floor of the structure. This enclosure was located near the "upstream" corner of the structure. Failure occurred at the upstream end of the structure due to scour to depths below post embedment.

Lesson. This structure was exposed to extreme high velocities. Structure failure occurred because of four basic reasons. First, the enclosed lower area utility room created even higher localized velocities than already present as the floodwater flowed around the obstruction. Second, the enclosed area was near the "upstream" corner of the structure so the localized velocity increase occurred near the slab edge where scour could occur beneath the slab. Third, perimeter footings were not in place under the slab-on-grade to prevent scour beneath the slab. Fourth, the post embedment depth was not deeper than the scour depth. These factors combined to create a situation conducive to massive scour and failure. The eastern portion of the structure, which did not have an enclosed area, functioned successfully.

Looking at the collapsed portion of the structure. The collapsed portion is at the left.
The river is behind the structure

STRUCTURE 60. This structure was a single-family home with its first floor elevated about 8 feet above a concrete slab-on-grade. This home sat directly east of Structure 59 and about 30 feet from the San Jacinto River. It was elevated on 10-inch by 10-inch wooden posts spaced from 12 to 16 feet apart. The entire area beneath the first floor was open for unobstructed floodflow. This home was not damaged to any great extent. The only visual damage was a small amount of scour along the north edge of the slab.

Lesson. This flood proofing system functioned very well. This appears to be due to the lack of a localized velocity-increasing mechanism, such as a lower enclosed area, that would create a situation conducive to large amounts of scour. This structure should be retrofitted with perimeter footings around the slab-on-grade embedded to below scour depth to prevent the amount of scour that did occur.

Looking away from the river at the structure. Note the area beneath the structure is completely open.

STRUCTURE 61. This single-family home was elevated on 8-inch by 8-inch wooden posts spaced about 10 to 13 feet apart. The posts were embedded about 3 to 4 feet below grade. The entire lower area was enclosed and used as living space. The structure was about 150 feet from the San Jacinto River. The floodwater depth in the area was about 6 feet. The first floor was elevated about 8 feet above grade. A concrete slab-on-grade was in place. Concrete was not placed around the base of the wooden posts. Failure occurred due to scour to depths greater than the bottom of the posts. Friction post support was removed due to the scour.

Lesson. Failure of the system occurred due to high localized velocities. Even though the structure was 150 feet from the riverbank, the localized velocities created by the water flowing around the enclosed lower area created conditions enabling localized scour to occur to depths that caused failure. The main deficiencies with this system are the enclosed lower area, which created high localized velocities; the lack of adequate post embedment depth; and the lack of perimeter footings beneath the slab-on-grade to prevent scour under the slab.

STRUCTURE 62. This single-family home was elevated on 8-inch by 8-inch wooden posts about 10 to 13 feet apart. The first floor was about 9 feet above the concrete slab-on-grade. The home was about 40 feet from the San Jacinto River. No damage occurred to the structure. No evidence of any scour was present.

Lesson. This flood proofing system worked well. No scour was evident, probably because of the "shield" effect of a row of trees and brush to the left (upstream) side of the structure. These trees apparently provided protection from the high velocities so scour did not attack even the slab-on-grade. The lack of an enclosed obstruction in the lower area prevented the creation of high localized scour-producing velocities. Scour was evident to the left of the row of trees.

Looking toward the river at the structure. Note the trees on the left that apparently protect this structure. Note, also the lack of any obstruction beneath the structure.

STRUCTURE 63. This single-family home was elevated about 8 feet from grade to the first floor. A concrete slab-on-grade was present. A closed-in lower area utility room was also present. The structure was about 150 feet from the San Jacinto River. Trees and brush were located between the river and the structure. No major scour was evident.

Lesson. This flood proofing system worked well, with no apparent damage. This structure was located just west of Structure 61, which failed. Two basic reasons exist for why this system worked and that for Structure 61 did not. First, the trees and brush provided velocity "protection" to Structure 63. Second, the enclosed area was set back about 10 feet from the edge of the concrete slab-on-grade so any localized high velocities caused by the enclosed obstruction acted upon the slab-on-grade and not on the scourable soil at the edge of the slab.

STRUCTURE 64. This single-family home was elevated 13 feet 5 inches above grade on columns made of 12-inch by 16-inch concrete block. The columns were grouted with concrete and contained six rebars each running the full column length and tying into the foundation. The foundation was a "floating concrete slab" comprised of 18-inch-deep by 12-inch-wide reinforced concrete beams buried just below grade horizontally with a 6-inch concrete slab on top of the beams at grade. The columns were about 11 to 12 feet apart. The structure was about 150 feet from the San Jacinto River. Debris accumulated at the northeast corner of the structure. This debris obstruction, coupled with high-velocity floodwater, caused hydrodynamic force to slightly tip this floating structure. Considerable scour occurred around the debris accumulation.

Lesson. This structure received relatively little flood-related damage during this event. The home was realigned and the scoured area filled. Even with this "success," this flood proofing system should not be promoted. The risk to this structure is great for two reasons--both related to debris accumulation. First, severe debris accumulation, coupled with hydrodynamic force, could tip over the structure. Second, scour could severely undermine this structure’s foundation because of debris accumulation, also resulting in the structure tipping.

Looking NW at the structure. The San Jacinto River is at far right outside of the photograph.

<u>STRUCTURE 65</u>. This single-family home was elevated on wooden posts. It was located a considerable distance from the San Jacinto River. Damage occurred to this structure because of localized scour and shallow post embedment depth coupled with concrete placement around the post only at the surface. A portion of the lower area was enclosed, creating a condition for high localized velocities and scour.

<u>Lesson</u>. Damage occurred with this system because of the enclosed lower area, which created high localized velocities and scour, and the extremely shallow post embedment depth. If the posts had been embedded to a greater depth and placed in concrete and the enclosed area had not been present, this structure would probably have sustained no damage.

Looking at the structure.

Looking at the structure's shallow post embedment depth.

STRUCTURE 66. This single-family house was elevated about $9^1/_2$ feet from first floor to concrete slab-on-grade by 10-inch by 10-inch wooden posts located from 10 to 12 feet apart. The posts were embedded from 6 feet to 10 feet below grade without concrete. Floodwater depth was about 6 feet. An enclosed utility area was located in the central portion of the lower area. The structure was located about 40 feet from the San Jacinto River. Failure occurred due to scour.

Lesson. This structure had an enclosed area in the central portion of the lower area between the slab-on-grade and the first floor of the home. This enclosed area was conducive to creating high localized velocities. Its location, however, in the central part of the lower area surrounded by a concrete slab for some distance proved in other structures to be not nearly as damaging due to scour as when located near the upstream edge of the slab. Apparently, the tremendous scour that occurred at this structure was aggravated by the enclosed area but was created mostly by the structure's location along the river. Perimeter footings under the slab-on-grade would have greatly reduced the scour even in this apparently bad location. Post embedment depth obviously should have been deeper. For definite protection from this type of damage, piles driven to below the scour depth would have been the ultimate solution.

Looking at tilted structure as a result of scour under the left portion of the structure.

STRUCTURE 67. This single-family home was located about 100 feet from the San Jacinto River. The home was slab-on-grade construction, with the first floor elevated on extended foundation walls and the lower area completely enclosed except for doors and windows. No evidence of any scour was present. One side of the home collapsed, probably because of hydrodynamic force against the extended foundation wall. No reinforcement or grouting was evident in the foundation wall. Flood depth in the area was about 11 feet above grade.

Lesson. This flood proofing system failed for basically two reasons. First, the lower area was completely finished, creating high localized velocities that resulted in extensive damage to the interior. Second, extended foundation walls were used, inappropriately, in high-velocity areas, subjecting the structure to hydrodynamic force.

Looking at the failed structure.

STRUCTURES 68, 69, 70, 71. These structures were all single-family homes. Severe erosion occurred because of deep floodflows at high velocity as floodwater from the San Jacinto River exited the channel to flow overland across a peninsula created by large bends in the river channel. As seen in the photograph, the homes were totally destroyed.

Lesson. No flood proofing system can withstand erosion such as that experienced here. Construction of any type in an area where extremely high velocities can occur is not advised and reflects extremely poor judgment.

Looking across the area previously occupied by these structures.

FLORIDA PANHANDLE

During the fall of 1995, hurricanes struck the Florida panhandle with hurricane force winds, wave runup, heavy rainfall, and flooding. Development along the shoreline sustained damage from flooding, wind, erosion, and hydrodynamic force.

PANAMA CITY, FLORIDA

STRUCTURES 72, 73. These structures were located directly on the beach. They were elevated on extended foundation walls made of concrete block with slab-on-grade construction and shallow footings. The lower (at grade) floor was finished with large glass windows facing the ocean. A concrete slab seawall was located between the structures and the ocean. Floodwater damaged the lower at-grade first-floor level. Hydrodynamic force broke the windows. Scour under the slab-on-grade foundation did not occur because of the presence of the seawall.

Lesson. Slab-on-grade construction with shallow footings should not have been used in this location because of the enormous potential for scour. The lower floor should not have been developed because of the great potential for flooding from hurricane force wave runup. These structures, as built, were saved from major structural damage by basically two items. One, the presence of the large plate glass windows on the lower floor broke under wave force, allowing flood damage to occur but reducing the potential for complete wall failure due to hydrodynamic force. Two, the presence of the seawall protected the slab-on-grade foundation from extensive scour, which would have allowed substantial structural failure to occur.

Looking at the slab-on-ground structures and the seawall.

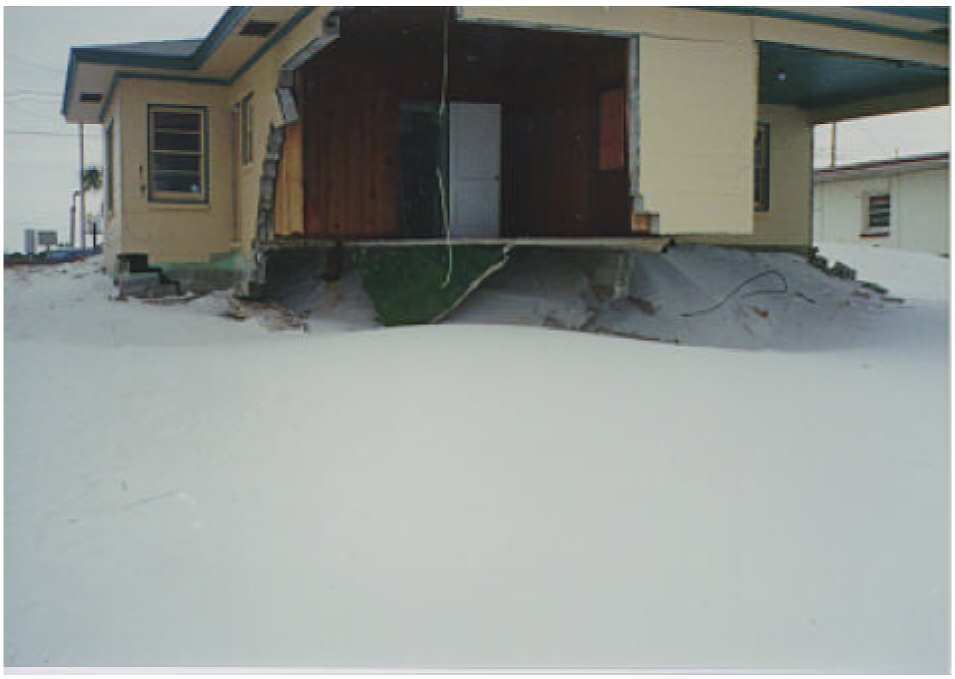
STRUCTURE 74. This structure was elevated on extended foundation walls on shallow footings with the first floor consisting of concrete on sandfill placed within the perimeter formed by the extended foundation walls. The structure was located directly on the beach. Scour undermined the shallow footings along one side of the structure, causing collapse of the extended foundation wall, erosion of the sandfill placed within the perimeter formed by the extended foundation walls, collapse of the concrete floor, and subsequent failure of the concrete block wall and also the roof. Floodwater inundated the first floor.

Lesson. Four basic problems were present with this structure. First, the footings were too shallow, allowing scour to undermine them. Second, extended foundation walls, which are not appropriate for coastal areas subject to hydrodynamic force, were used. In this particular case, failure did not occur because of extended walls, but they made the structure highly susceptible. Third, the concrete slab for the first floor was supported by sandfill. When the perimeter wall failed, erosion of the sandfill occurred, causing the floor to collapse. The floor should have been supported on piles driven to a depth below the potential scour, or the perimeter footings supporting the extended foundation walls should have been constructed to below-scour depth. Fourth, the structure was not elevated enough to prevent floodwater damage. Structures such as this in this location need to be elevated on piles.

Looking at the structure with the beach in the background.

STRUCTURE 75. This structure was very similar in construction to Structure 74, and similar failure occurred. The structure directly fronted the beach, had extended foundation walls on shallow footings with some elevation, and had a first floor slab on sandfill retained by the perimeter extended foundation walls. In the case of Structure 75, the failed wall directly faced the beach; the failed wall on Structure 74 did not. Location of the failed wall may have caused failure of the structure due to both scour under the footings and hydrodynamic force against the extended foundation walls. Erosion of the sandfill allowed failure of the concrete floor slab. Floodwater inundated the first floor.

<u>Lesson</u>. This structure had the same basic four problems as Structure 74--shallow footings, extended foundation walls, concrete slab on sandfill, and inadequate structure elevation. Extended foundation wall failure was due first to scour and then to hydrodynamic force. The roofline on this structure was maintained, unlike that on Structure 74, probably because of the presence (in the middle of the structure) of the concrete block support for the floor and interior wall. This example shows the importance of multiple supports beneath a structure in an area subject to excessive scour. As stated for Structure 74, a structure with extended foundation walls, shallow footings, and a concrete slab on sandfill is definitely not appropriate at this location.



Looking from the beach at the structure.

<u>STRUCTURE 76</u>. This structure was located adjacent to Structure 75, so it was subjected to similar forces. Structure 76 differed from Structure 75 in its support system. Structure 76 was supported on wood piles embedded to below the scour depth that occurred in the Fall of 1995. Structural failure of this structure did not occur, although the structure was inundated by floodwater.

<u>Lesson</u>. This structure performed well except for one problem--it was elevated to an insufficient height to prevent damage from floodwater. The structure support system of wood piles

functioned well. The concrete first floor slab remained intact because of the adequate wood pile support even though the sand had been removed from beneath the slab.

STRUCTURES 77, 78 . These structures directly faced the beach. Structure 77 was a one-story residential structure constructed on extended foundation walls. Failure of the footings and extended foundation walls occurred because of the combination of scour and hydrodynamic force. This was followed by first-floor concrete slab failure, wall failure, and roofline failure. Floodwater inundated the first floor. Structure 78 was a two-story residential structure constructed at basically the same first-floor elevation as Structure 77. Structure 78 was supported on wood piles embedded below the scour depth. No structural failure occurred. The first floor was flooded.

Lesson. Comparing Structures 77 and 78, located adjacent to one another, shows the inherent problem with shallow footings, extended foundation walls, and a first- floor concrete slab supported by sandfill. Scour undermined the shallow footings of Structure 77, causing, with hydrodynamic force, the failure of the extended wall foundations. This allowed erosion of the sandfill supporting the first-floor concrete slab and failure. In contrast, Structure 78, supported on piles embedded below scour depth, sustained no structural damage. Both structures were flooded because of inadequate elevation.

Looking at the structure with extended foundation walls on the left
and at the structure with a pile support foundation on the right.

STRUCTURE 79. This structure was a two-story residential structure facing directly toward the beach. It was elevated higher than many along the beachfront. It was supported by extended foundation walls on shallow footings with a concrete slab placed on sandfill for support. Failure occurred because of failure of the footings, walls, and slab. Failure due to tremendous wind damage and hydrodynamic force was also apparent. This structure was totally destroyed.

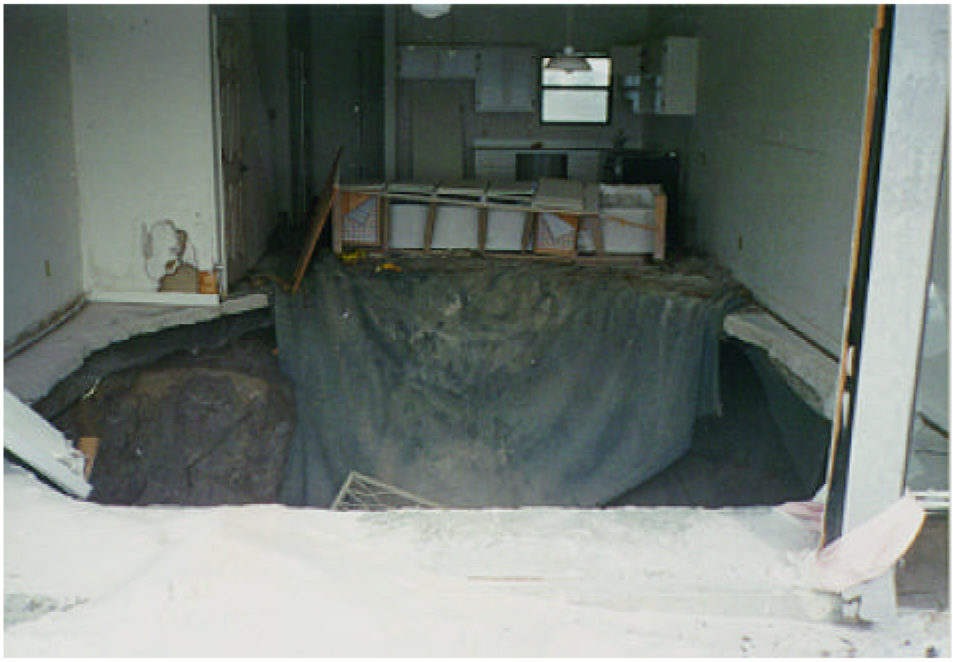
Lesson. This structure is discussed because it sustained massive damage even though it was elevated as much or more than most structures along this reach of beachfront. Failure probably started to occur because of scour beneath the shallow footings and hydrodynamic force against the extended foundation walls and the structure itself. Erosion of the sandfill caused concrete slab failure. Failure of these foundation elements substantially weakened the structural integrity of the wood-frame structure, allowing wind and hydrodynamic force to cause a near total destruction. A foundation of piles embedded below scour depth, with the piles extending to the roofline for proper structure/footing tie-in, and hurricane fasteners would probably have allowed this structure to sustain minimal damage.

Looking at the totally failed structure from the beach.

STRUCTURE 80. This structure was a two-story reinforced concrete multifamily dwelling. It was slightly elevated on wood piles. The piles were located beneath the bearing walls of the structure but not under the concrete slab on the first floor. The slab was supported by sand fill. Damage occurred due to erosion of the sandfill beneath the concrete slab, which allowed the concrete slab to drop. The structure was not elevated enough to prevent flood damage. Other than the floor damage, no basic structural damage occurred.

Lesson. The structure performed adequately except for two reasons. One, the structure was not elevated high enough to prevent flooding. Two, the concrete slab on the first floor was supported only by sandfill. When the sand eroded, the floor collapsed. Floor collapse could have been prevented by placing supporting posts beneath the concrete slab or by using rebar to support the floor from the piles located beneath the bearing walls.

Looking at the structure. Note that the building structure did not collapse due to the pile support foundation.



Looking inside the structure at the collapsed floor due to scour of the sand beneath the slab-on-grade floor

Looking inside the structure at the collapsed floor due to scour of the sand beneath the slab-on-grade floor.

STRUCTURE 81. This residential structure was located about two blocks from the beach. The first-floor living area was well elevated. The lower (at grade) area was fully enclosed with non-breakaway walls and was used as a garage and utility room. Between this structure and the beach was a multistory residential structure. Structure 81 endured the storm forces well.

Lesson. This structure was recently constructed. It had adequate elevation and was constructed to state-of-the-art building codes. Because of its location two blocks from the beach and behind a large multistory building that may have provided some protection from hydrodynamic force, the degree of hazard was lower than had it been located directly on the beach. A note of caution with this structure is the enclosed lower area. This type of enclosed construction, unless the walls are able to break away during a hurricane event, subjects the structure to hydrodynamic force and the potential for foundation scour due to the obstruction to waterflow caused by the enclosed walls at ground level.

Looking at the structure. The beach is in the far background behind the multistory building.

STRUCTURE 82. This multistory residential complex was elevated on reinforced concrete columns that sustained minimal damage. It was located directly facing the beach. The structure's first floor was elevated several feet above beach level and was used for automobile parking. The first habitable floor was two floors above the ocean level. The structure was protected from scour by a concrete wall.

Lesson. This structure was successful for two basic reasons. It had both proper elevation and proper scour/erosion protection. The first damageable floor was well above the flood level since it was two floors above the ocean level. The first floor was occupied by automobiles which can easily be moved to a nonhazard area with proper warning time. Scour did not pose a problem because of the wall and the proper column embedment depth.

Looking from the beach at the structure.

STRUCTURE 83. This structure was a motel complex consisting of two buildings with two habitable stories each. A concrete swimming pool was located between the two buildings. The structures were elevated above the beach but not enough to prevent first-floor flooding. The structure directly faced the beach. Support was provided by 8-inch wooden piles approximately 9 feet on center. These piles were braced by wooden "x" bracing. The floor of each building was a concrete

slab placed on sandfill. From visual inspection, it could not be determined if rebar was present in the concrete slab. Severe scour occurred around and beneath the buildings to the extent that the buildings, which prior to the event appeared to be “at grade,” were, after the event, elevated about 5 feet above the grade after scour. The concrete swimming pool, which was supported on sandfill, had dropped several feet from its pre-event elevation because of scour of the sandfill

Lesson. Severe scour occurred around and under these structures during the event. The wood piles appeared to be improperly sized, since some were visibly leaning under the weight of the buildings without sandfill support. The “x” bracing on the piles may have saved the building from collapsing. This shows the need not only for proper embedment depth of posts or piles but also for proper size of posts or piles for needed strength. In this case, where sandfill appears to have been factored in as a part of the building support/stability system, a protection wall around the building that could have withstood the scour hazard and hydrodynamic force should have been built. The most proper design, however, would have been to elevate the buildings on larger diameter piles that were completely independent of sandfill for added support to the buildings.

Looking at the structure and beach. Prior to the event, the “grade” elevation at the far right extended toward the beach and under the structure.

Looking from the beach at the structure. Note the collapsed swimming pool between the structures.

STRUCTURE 84. This structure number represents structures that directly faced the beach but were set back a considerable distance, were elevated relative to sea level, and have been protected by a sand dune with natural vegetation. In this case, the dune appeared to be natural but could just as well have been manmade. The combination of higher elevation, greater distance from the beach, and/or existence of a natural dune provided good protection to these structures.

Lesson. "Conventional" construction techniques in the structure itself are often very adequate to mitigate hazards from floods, erosion, and hydrodynamic force if other nonstructure-related techniques are employed. In this case, constructing structures on higher ground is a large step toward hazard mitigation in the form of reduced flood damages. A large setback allows room for either a natural or a manmade dune to be located between the ocean and the structure. This can diminish or eliminate hydrodynamic force on the structure and the potential for scour at the structure.

Looking along the beach at the structure and the dune. Note the structure elevation and the dune protection.

Looking along the beach at the structures and the dune. Note these structures are not elevated as high as those in the above photograph but the dune has much more vegetation.

PENSACOLA, FLORIDA

<u>STRUCTURE 85</u>. This structure, which was constructed on a barrier island, faced the beach. The structure was a three-story wood-frame building with the first floor elevated by wood-frame construction on shallow footings. Very high flood velocities were experienced in this area as floodwater flowed across the barrier island. Floodwater depths of about 4.5 feet were directly impinging on the structure. Localized scour occurred, which undermined the shallow foundation and caused one-fourth of the structure to collapse.

<u>Lesson</u>. Two basic factors caused the collapse of one-fourth of the structure. First, the construction on the barrier island placed the structure in jeopardy due to high-velocity floodwater, creating both a hydrodynamic force hazard and a scour hazard. Construction in areas such as this should be avoided. Second, the structure foundation that was situated in sand should have been much deeper to resist the forces of erosion caused by the high velocities and compounded by the obstructive nature of the structure.

Looking at the structure from the beach.

STRUCTURE 86. This structure, which directly fronted the beach, was a one-story, single-family wood-frame home elevated approximately 8 feet on wooden piles. It had an enclosed lower area for storage of utility items. Embedment of the wooden piles was adequate to withstand scour from this event. This structure survived well, as did other structures of this type similarly elevated.

Lesson. This structure survived well in this event. However, the enclosed lower area could have created a problem due to the obstructive effect of the floodwater creating hydrodynamic force against the enclosed area and higher localized velocities as floodwater flowed around the enclosed area. This effect could cause excessive localized scour to depths not anticipated in sand, undermining pile supports and causing failure. It is best in warm climates, such as occurs in Florida, to have lower level storage areas enclosed with “jail-type” spaced bar construction so floodwater can flow through, eliminating hydrodynamic force and scour potential.

Looking along the beach at the structure.

STRUCTURE 87. This was a two-story, single-family residential structure elevated on 12-inch-diameter wooden piles. The piles were of such length that they extended from embedment depth up to the roofline so the entire structure was tied together by means of the wooden piles. Hurricane-type steel fasteners were in place. The first floor was elevated 8 feet above grade, with the lower area entirely unobstructed. The structure was under construction at the time of the event.

Lesson. This structure was designed to accommodate hurricane hazards from wind,

flooding, and scour. One possible weakness was observed at the intersection of the main floor with the wooden piles. The wooden piles were notched to accommodate a resting place for the main floor sills to the extent that the 12-inch-diameter wooden piles were reduced in diameter to approximately 6 inches. This weakens the effectiveness of the piles' ability to bond the entire structure together in terms of the ability to withstand hurricane force winds.

Looking at the structure with the beach in the background.

STRUCTURE 88. This structure was a single-family, wood-frame home elevated on columns made of concrete block with a one-half-inch rebar grouted into each hole of the concrete block. This made a reinforced concrete block column for use in elevating the structure about 8 feet above grade. The structure was about 300 feet from the beach on the landward side of a beachfront street. The structure survived the event well, except for the reinforced concrete block columns, which sustained severe cracking apparently from the torsion effect of the hurricane force wind against the structure. No "x" bracing was used between the columns. The columns appeared to be close to failure.

Lesson. Reinforced concrete block columns of this design are not appropriate in coastal areas where high wind forces occur against a structure. The concrete block columns should have contained more rebar in order to provide rigid strength against the hurricane force winds. The best alternative is to use piles that have the ability to resist this type of force without becoming damaged.

Looking at the structure.

Looking at the column support that was nearing failure.

<u>STRUCTURE 89</u>. This structure was a new, one-story, single-family home elevated on wood piles. It directly fronted the beach. The structure employed proper elevation, wood piles for support, proper pile embedment depth, minimal floodwater obstruction, and proper wind proofing. The structure received minimal damage during the event. It was the only structure in the reach that survived.

<u>Lesson</u>. This structure survived the event well because it incorporated proper design and construction to withstand hurricane force winds, flooding, and hydrodynamic force associated with such a storm.

Looking at the structure. Note the beach at the left. Note also the absence of adjacent structures, which had been destroyed and removed.

EASTERN CALIFORNIA AND WESTERN NEVADA

Severe flooding occurred in January 1997 as a result of heavy snowfall followed by heavy rainfall in the Sierra Nevada Mountains of eastern California and western Nevada and the adjacent "foothills" of eastern California. The occurrence of heavy rainfall on the already present snowpack created tremendous runoff, resulting in flooding along the Sacramento and San Joaquin Rivers and their mountain tributaries in California and along rivers such as the Truckee in western Nevada.

SACRAMENTO, CALIFORNIA

STRUCTURE 90. This structure was a one-story single-family residence with a slab-on-grade foundation. The structure was located about 70 feet from the Sacramento River between the river and a levee. It was oriented with its largest dimension parallel to the river. The Sacramento River at this location was above flood stage for about 2 weeks. There was ample warning time prior to the flooding. The structure was protected by a floodwall made of 100 percent grouted concrete block. Horizontal and vertical steel reinforcement was in the wall. The original wall was built prior to 1986. Subsequent to 1986, the wall was extended upward 26 inches with $^{3}/_{8}$ inch rebar located every 32 inches to tie the new wall to the old wall. The maximum height of the wall above ground was 64 inches. The minimum distance of the wall to the structure was 3 feet. The wall surrounds the structure on three sides. The wall tied into the levee, a "mainline" levee protecting the City of Sacramento, which provided protection on the fourth side. The floodwall had two openings in it on that portion paralleling the river. The openings were 3 feet and 8 feet wide. The 3-foot-wide opening was closed with a single piece of $^{5}/_{8}$ inch plywood attached by screws to the concrete block floodwall. Caulking was applied to the joints, and sandbags were piled at the bottom on both the protected and the river sides. The closure was 56 inches high. Plastic sheeting was placed over the closure on the river side. The 8-foot-wide closure was constructed similarly, with the exception that it was made of double 1-inch-thick plywood with bracing on the protected side consisting of 2- inch by 4-inch lumber placed horizontally and vertically at the center of the closure with a diagonal 4-inch by 4-inch brace from the center of the wall to the concrete floor. A sump pump was present near the 8-foot-wide closure. The 1997 flood was up about 40 inches on the floodwall. The owner/resident waged a flood fight during the flood.

Lesson. This flood proofing system failed, inundating the structure up to the level of the flood. Failure occurred for basically two reasons. Excessive water seepage occurred at the 8-foot-wide closure due to inadequate sealing on the bottom and sides of the closure. To prevent this seepage, this closure, because of its width, should have been constructed of more rigid material such as aluminum with manufactured sealing membranes that would have increased sealing capability with increased hydrostatic force. This large closure was very critical and needed a "state-of-the-art" closure. The excessive seepage exceeded the capacity of the sump pump, causing water to accumulate on the concrete floor. This sump pump was powered by an electrical cord lying on the floor. The seepage water covered the cord, causing a "short" to occur and stopping the sump pump. Before power could be restored, seepage water continued to accumulate and flowed about 40 feet along the wall to a location where excavation had occurred for utility work sometime prior to the flood. The excavated area had not been properly compacted. The wetting of the poorly compacted excavated area and the hydrostatic force of water 40 inches high on the wall created "piping" that caused massive failure under the wall. The owner/resident was fighting the flood at the time of failure. In this case, he was able to escape because the fourth side of the protection was the "mainline" levee that provided a nearby safe evacuation route. If the floodwall had surrounded the structure and floodwater had surrounded the floodwall, no safe excavation route would have been available. This is a large concern when employing flood proofing measures such as levees, walls, or dry flood proofing where sump

pumps are needed to evacuate seepage water and rainfall and owners tend to remain onsite to flood fight. For safety reasons, flood proofed structures should always be evacuated prior to being surrounded by floodwater. To do this, a fail-safe sump pump system needs to be employed--one that has redundancy so if one system fails another will come “online” automatically with or without electrical power. Another alternative is to manually switch the power source for the sump pump from an electric powerline source to either battery or generator, depending on the anticipated length of flood.

Looking along a portion of the floodwall. The failure under the wall occurred in the immediate foreground. Note the largest closure at the right of the structure. Also note the Sacramento River in the background.

Looking at the largest closure structure and sump pump. Note the electrical cords on the concrete floor.

STRUCTURE 91. This was a multistory floor, single-family, slab-on-grade structure located about 30 feet from the Sacramento River between the river and a “mainline” levee that was located about 50 feet from the structure. The structure was protected by an earthen levee located between the river and the structure and tying into the mainline levee. The levee had been in place about 15 years. Levee compaction was questionable.

Lesson. The flood proofing measure failed due to overtopping of the levee. Sandbags had been placed on top of the levee but were not able to prevent overtopping and erosion of the protected side of the levee as water flowed over the top. More levee erosion would have occurred, leading to levee breaching, if the protected area had not been so small, allowing for rapid equalization of the water surfaces on both the protected and unprotected sides of the levee. Obviously, this levee was not high enough since it was overtopped in 1997 and also in 1986. The real lesson to be learned at this structure and also at Structure 90 is the choice of flood proofing measure. In these cases, the site location on a narrow strip of land between a major river and a “mainline” levee should be strongly considered when selecting a flood proofing measure. The ultimate flood proofing measure is relocation.

Elevation or wet flood proofing, with the protected level no lower than 1 foot above the top of the mainline levee, would be the next choice. Barriers such as levees, walls, or dry flood proofing are not a good choice in locations such as the locations of Structures 90 and 91 because of the large height required for these measures to achieve protection to at least 1 foot above the top of the adjacent "mainline" levee.

Looking along the overtopped levee. Note the Sacramento River at the left and the low elevation of the developed first floor of the structure relative to the river elevation.

RENO, NEVADA

<u>STRUCTURE 92</u>. This structure was a multistory public building located within about 100 feet of the Truckee River. The building was constructed in 1996. The building walls were constructed of reinforced concrete. Ample warning time prior to flooding was present. The lower level was flood proofed by wet and dry flood proofing. The wet flood proofed area was used for building access and vehicle parking. The remainder of the lower level was dry flood proofed by using waterproofed reinforced concrete with a state-of-the-art closure panel consisting of metal construction with a pneumatic seal on all sides except the top, which left a gap in all closures of about 8 inches.

Lesson. The wet flood proofing measure functioned properly, with apparently little damage in this part of the lower level. The dry flood proofing measure however, failed. This measure was designed for 1 foot above the 100-year flood. The flood event of January 1997 exceeded that level. Floodwater overtopped the closure panel completely, inundating the protected area. Obviously, the closure panels and the reinforced concrete walls should have been designed for a higher level of flooding that would have completely closed all openings. The state-of-the-art metal panels with a pneumatic seal functioned as designed without damage. They were simply not high enough. In addition, it was reported that floodwater was already about 1 foot deep in the protected area before floodwater overtopped the closure panels, indicating water was leaking through the waterproofed reinforced concrete. The most reliable waterproofing method for reinforced concrete is to "sandwich" a nonpermeable membrane between the layers of concrete. No damage was apparent to the actual reinforced concrete wall due to hydrostatic force.

Looking at the structure. The Truckee River is immediately to the right.
The flood proofed floor is at the automobile level.

Looking at a doorway into the "protected" area. Note the state-of-the-art pneumatic seal closure at the left in its storage position. Also note the gap between the top of the closure and the top of the doorway.

<u>STRUCTURE 93</u>. This structure was a single-story, slab-on-grade building located about 50 feet from the Truckee River. It was built in 1989 just downstream from a city bridge over the river. It was flood proofed by elevation on fill to a level 2 feet above the 100-year flood. A flood fight was waged with sandbags and plastic sheeting at openings on the upstream side of the building. The downstream side of the building was higher than the floodwater.

<u>Lesson</u>. This structure and its contents had minimal damage due to the flood proofing measure of elevation on fill and the flood fight. The lesson for this structure consists of four parts. First, the flood proofing measure enabled a flood fight to be successful. Second, a decision had to be made based on upstream flood information that a successful flood fight was possible while still keeping safety in mind for the flood fight personnel (since a basic parameter of flood proofing is to evacuate). Third, the impact of debris in the upstream bridge needed to be considered. This was evidently overlooked when the flood proofing elevation was selected. In the flood event, the upstream side of the bridge filled with debris to the extent that floodwater was forced out of the channel and onto the street just upstream from the structure at an elevation higher than the computed water surface elevation for a flood of this magnitude without the obstructive effect of the bridge. The fourth part of the lesson concerns the value of the contents in the structure. The contents consisted of $25 million worth of nonreplaceable antique automobiles. Contents that are nonreplaceable should always be located in a flood-free location.

Looking from the upstream street downstream at the structure.
The doors in the background are one of the flood fight locations.

<u>STRUCTURES 94, 95</u>. These structures were both slab-on-grade commercial buildings located several hundred feet from the Truckee River. The area was subject to only shallow flooding. These structures are presented to illustrate a type of earthen embankment that can be very effective in flood proofing against relatively shallow, short- duration floods. Structure 94 had been landscaped well to blend into the surroundings and be aesthetically pleasing. This embankment was a permanent flood proofing measure. The embankment protecting Structure 95 had just been constructed. It could be removed after the flood event or remain as a permanent measure. Sandbag closures across vehicle access routes were necessary.

<u>Lesson</u>. These flood proofing measures were successful. Earthen embankments, especially in shallow-depth flood areas of short duration, can be quite effective if placed on a permanent or temporary basis. Obviously, all parts of an earthen embankment flood proofing measure such as interior drainage, closures, and so forth must be present and functional.

Looking along the earthen embankment with Structure 94 on the right. Note the raised handrail as the pedestrian entry to the building passes over the embankment.

Looking at the recently constructed earthen embankment protecting Structure 95. Note the plastic sheeting at the far right that was placed over the embankment's unprotected side and held in place with sandbags to provide impermeability to the embankment.

LOWER PLATTE RIVER, NEBRASKA

Serious ice-jam flooding occurred along the Lower Platte River in Eastern Nebraska in February 1997. The ice-jam flooding resulted from late winter snowmelt runoff entering the river prior to breakup of the winter accumulation of ice. Due to the presence of ice in the river, ice jams occurred, causing serious flooding in localized areas. The flooding in some areas also contained large amounts of thick river ice chunks, which added to the associated hazard.

STRUCTURE 96. This structure represented several two-story, dormitory-type structures elevated on reinforced concrete posts that were tied to footings thus forming piers.

The posts were 16 inches in diameter and were located 16 feet apart. They were composed of concrete reinforced with six No.6 vertical rebars and eight No. 7 vertical rebars. The posts rested on reinforced concrete footings varying in size from 8 feet by 8 feet by 16 inches thick to $5^1/_2$ feet by $5^1/_2$ feet by 14 inches thick. The footings were tied to each post with rebar. The footings were 4 feet in the ground. The lowest elevation of the elevated building was 1 foot above the 100-year flood. A utility corridor existed, measuring 5 feet by 5 feet and extending from the ground to the elevated building. This corridor was waterproofed, was built of reinforced concrete to resist hydrostatic force and had a watertight closure door used for access.

During the 1997 flood event, about 3 feet of floodwater inundated the area beneath the elevated buildings. Massive ice blocks also floated beneath the elevated buildings, directly impinging upon the posts. Floodflow velocity was moderate. No damage occurred due to either floodwater or the impact of the ice blocks.

Lesson. This flood proofing system performed very well in this flood event. The buildings were elevated enough to be above the flood elevation and the posts were strong enough to withstand the impact of floating ice blocks without damage. Erosion was not a factor for the event.

Looking at one of the elevated buildings.

Looking at the massive ice blocks that passed through the area.

RED RIVER OF THE NORTH, MINNESOTA AND NORTH DAKOTA

Historic flooding occurred along the Red River of the North in Eastern North Dakota and Western Minnesota in April 1997. The flooding resulted from the melting of an extremely heavy snowpack that accumulated during the winter of 1996/1997.

EAST GRAND FORKS, MINNESOTA

STRUCTURE 97. This structure was a one-story, single-family residential building with a basement. It had an attached double car garage on its east side. It was constructed about 1990. The structure was wood-frame construction resting on foundation walls of reinforced poured concrete. The soil surrounding the structure was a mixture of silt and clay. The structure was about 350 yards from the Red River and was protected by a “mainline” levee located close to the river channel bank. The structure was dry flood proofed. The basement floor and walls were constructed of 8-inch-thick concrete with $^{1}/_{2}$-inch rebar located horizontally and vertically every 6 inches. A nonpermeable neoprene membrane was located in the middle of the 8-inch-thick walls and floor. The structure did not have a sump pump. Velocity was not a factor. The first floor was about 3 feet above ground and about 2 feet above the 100-year flood.

Lesson. This structure was dry flood proofed at a far greater expense than conventional construction of adjacent foundation walls and floors in the neighborhood that were not flood proofed. Only one mistake was made, but it proved to be very costly. The effects of hydrostatic force were considered structurally in the strength of the walls and floor of the basement but not in the ability of the structure to resist uplift force (buoyancy). The designer of this flood proofing system specified that in order for the structure to resist buoyancy, the structure owner needed to fill the basement with a minimum of 42 inches of water. The structure owner chose not to do this. Upon failure of the mainline levee, floodwater surrounded the dry flood proofed portion of the structure and entered the garage, which had a floor at grade. The flood peak was 20 inches deep on the garage floor but was still below the design level of the dry flood proofing measure. However, within 12 hours of floodwater surrounding the structure, the hydrostatic force lifted the west edge of the structure as much as 4½ feet. The eastern edge of the dry flood proofed part of the structure was held in place by the attached garage. Damage to the structure resulted from the unequal lifting of the structure (structural damage) and rupture of the utility lines that entered the basement (floodwater entry). Signs of an electrical fire in the outside panel box were evident, probably as the electrically charged underground lines were pulled from the panel box as the structure lifted. The irony of this example is that the structure that was dry proofed was considered severely damaged while adjacent structures that were not flood proofed only incurred damage due to water in basements but were structurally sound and could be reoccupied. This example points out the difficulty of dry flood proofing a structure with a basement because of the effects of hydrostatic force. In this case, at least five items should have been done further to help offset the effects of hydrostatic force while not purposely placing water in the basement. One, the soil around the basement wall should have been properly compacted to make the

soil as impermeable as possible. Two, a drain field should have been installed around and beneath the basement floor leading to a sump pump to reduce hydrostatic force buildup by evacuating water. Three, the design should have incorporated measures to ensure that the floodwater never touched the basement wall. Four, as part of the floor, a structural anti-buoyancy device consisting of basically a floor slab extending beyond the walls but tied to the floor with rebar so the weight of the soil would act to offset the hydrostatic force against the basement floor should have been installed. Five, "blowout plugs" should have been installed in the floor. These plugs are designed to withstand hydrostatic force but will "blow out" prior to hydrostatic force making the structure buoyant. Soil permeability is obviously very critical. In this example, a silt clay soil should have been able to resist saturation longer than 12 hours. Improper backfill material type and compaction adjacent to the structure may have been major components leading to such rapid saturation of this soil type. In this specific case, since the owner knew that items two through five were not part of the design, the basement should have been purposely flooded with at least 42 inches of water prior to evacuating the structure. This was done to a similarly flood proofed structure in the area and only minor water damage occurred to the unfinished basement.

Looking at the structure. Note the garage on the right that held that part of the structure down and the exposed basement wall on the left indicating the amount of lifting that occurred on the west side.

OAKPORT, MINNESOTA

STRUCTURE 98. This was a one-story, single-family residential building with full basement. The floor was about 1 foot above grade. This flood event was about 2 feet below the floor and about 1 foot below grade at the structure, making the floodwater at the peak a few feet from the structure. The soil was a very impermeable clay. The basement walls and floor were 8-inch-thick reinforced concrete with a drain network around the basement wall perimeter and under the basement floor leading to a sump pump. The walls contained No.4 horizontal rebars and No.4 vertical rebars spaced a maximum of 6 feet apart. Rebar overlapping was a minimum of 12 inches. The No. 4 rebars were placed 18 inches on center to tie the wall to the footing. Window wells constructed to the same specifications as the basement walls were present. A waterproofed membrane was not located in the basement walls or floor. The flood duration was about 7 days. The structure was about 1,000 feet from the Red River of the North.

Lesson. This flood proofing measure functioned well. The three reasons why this flood proofing measure was successful versus that for Structure 97 (which was unsuccessful) are as follows. One, the soil at Structure 98 was more impermeable. This was the main factor. Two, floodwater remained probably 10 to 15 feet from the structure so water could not easily penetrate between the soil and the structure. Three, a good drain network leading to a sump pump was in place. This allowed evacuation of the water that was able to penetrate the soil. It should be noted that concrete blocks should not be used in this dry flood proofing system because they do not provide the strength that a poured concrete wall provides.

CHAPTER 3 - FLOOD PROOFING PERFORMANCE SUMMARY

This chapter presents in tabular form data concerning each structure observed, the flooding source and date, the type of flood proofing measure used, and the actual performance of the measure. The data are presented twice so information can easily be sorted by community and by flood proofing measure. Table 1 presents the information sorted by community. Table 2 presents the information sorted by flood proofing measure. See Chapter 2 for a narrative description of the structure, the flood proofing measure used, and the “lessons” gained from observing how the measure worked when tested by flooding.

TABLE 1

SUMMARY OF FLOOD PROOFING PERFORMANCE
(Organized by Community)

Structure No.	Community	Structure Type	Flood Source	Flood Date	Flood Proofing Measure	Performance
1	Clive, IA	Residential	Riverine	May 1986	Dry flood proofing	Successful
2	Alma, MI	Commercial	Riverine	Sep 1986	Dry flood proofing	Overtopped
3	Midland, MI	Residential	Riverine	Sep 1986	Dry flood proofing	1>
4	Midland, MI	Residential	Riverine	Sep 1986	Dry flood proofing	Failed
5	Midland, MI	Residential	Riverine	Sep 1986	Dry flood proofing	Failed
6	Midland, MI	Residential	Riverine	Sep 1986	Dry flood proofing	Failed
7	Midland, MI	Residential	Riverine	Sep 1986	Dry flood proofing	Failed
8	Crystal, MN	Residential	Riverine	Jul 1987	Floodwall	Failed
9	Crystal, MN	Residential	Riverine	Jul 1987	Floodwall	Mostly Successful
10	Crystal, MN	Residential	Riverine	Jul 1987	Dry flood proofing	Failed
11	Crystal, MN	Residential	Riverine	Jul 1987	Floodwall	Failed
12	Crystal, MN	Residential	Riverine	Jul 1987	Floodwall	Failed

TABLE 1 (cont.)

Structure No.	Community	Structure Type	Flood Source	Flood Date	Flood Proofing Measure	Performance
13	Montgomery Co., TX	Residential	Riverine	Jun 1989	Earthen ring levee/ elevation--extended foundation walls	Successful
14	Montgomery Co., TX	Residential	Riverine	Jun 1989	Dry flood proofing	Successful
15	Montgomery Co., TX	Residential	Riverine	May 1989	Floodwall	Overtopped
16	Montgomery Co., TX	Residential	Riverine	May 1989	Dry flood proofing	Partially Successful
17	Montgomery Co., TX	Residential	Riverine	Jun 1989	Elevation--wood piles	Successful
18	Surfside Beach, SC	Residential	Coastal	Sep 1989	Elevation--steel columns	Successful
19	Surfside Beach, SC	Residential	Coastal	Sep 1989	Elevation--brick piers	Failed
20	Surfside Beach, SC	Residential	Coastal	Sep 1989	Elevation--block piers	Failed
21	Garden City, SC	Residential	Coastal	Sep 1989	Elevation--wood piles	Successful
22	Garden City, SC	Residential	Coastal	Sep 1989	Elevation--wood piles	Successful
23	Pawley's Island, SC	Residential	Coastal	Sep 1989	Elevation--wood piers	Failed
24	Pawley's Island, SC	Residential	Coastal	Sep 1989	Elevation--wood columns	Successful

TABLE 1 (cont.)

Structure No.	Community	Structure Type	Flood Source	Flood Date	Flood Proofing Measure	Performance
25	Pawley's Island, SC	Residential	Coastal	Sep 1989	Elevation--concrete piles	Failed
26	Debidue Beach, SC	Residential	Coastal	Sep 1989	Elevation--piles	Failed
27	Debidue Beach, SC	Residential	Coastal	Sep 1989	Elevation--concrete piers	Failed
28	Charleston Co., SC	Residential	Coastal	Sep 1989	Elevation--masonry piers	Failed
29	Charleston Co., SC	Residential	Coastal	Sep 1989	Elevation--masonry piers	Successful
30	Charleston Co., SC	Residential	Coastal	Sep 1989	Elevation--masonry piers	Successful
31	Charleston Co., SC	Residential	Coastal	Sep 1989	Elevation--wood piles	Successful
32	Charleston Co., SC	Residential	Coastal	Sep 1989	Elevation--wood piles	Successful
33	Charleston Co., SC	Residential	Coastal	Sep 1989	Elevation--wood posts	Successful
34	Charleston Co., SC	Residential	Coastal	Sep 1989	Elevation--wood piles	Failed
35	Charleston Co., SC	Residential	Coastal	Sep 1989	Elevation--wood piles	Failed
36	Charleston Co., SC	Residential	Coastal	Sep 1989	Elevation--wood piles	Failed
Structure No.	Community	Structure Type	Flood Source	Flood Date	Flood Proofing Measure	Performance
37	Charleston Co., SC	Residential	Coastal	Sep 1989	Elevation--masonry columns/wood piles	Successful

TABLE 1 (cont.)

38	Charleston Co., SC	Residential	Coastal	Sep 1989	Elevation--concrete block	Failed
39	Charleston Co., SC	Residential	Coastal	Sep 1989	Elevation--wood posts	Successful
40	Charleston Co., SC	Residential	Coastal	Sep 1989	Elevation--reinforced concrete columns	Successful
41	Charleston Co., SC	Residential	Coastal	Sep 1989	Elevation--wood piles	Successful
42	Charleston Co., SC	Residential	Coastal	Sep 1989	Elevation--wood piles	Failed
43	Crystal City, MO	Industrial/ Commercial	Riverine	Summer 1993	Levee	Failed
44	Herculaneum, MO	Residential/ Commercial	Riverine	Summer 1993	Floodwall	Failed
45	Barnhart, MO	Residential	Riverine	Summer 1993	Floodwall	Failed
46	Barnhart, MO	Residential	Riverine	Summer 1993	Elevation--extended foundation walls	Failed
47	St. Louis, MO	Commercial Government	Riverine	Summer 1993	Floodwall	Failed
Structure No.	**Community**	**Structure Type**	**Flood Source**	**Flood Date**	**Flood Proofing Measure**	**Performance**
48	St. Genevieve, MO	Commercial	Riverine	Summer 1993	Levee	Successful

TABLE 1 (cont.)

49	St. Genevieve, MO	Commercial	Riverine	Summer 1993	Wet flood proofing	Failed
50	St. Genevieve, MO	Commercial	Riverine	Summer 1993	Elevation--fill	Successful
51	St. Louis, MO	Residential	Riverine	Summer 1993	Elevation 2>	Failed
52	Nutwood, IL	Residential	Riverine	Summer 1993	Elevation--extended foundation walls	Failed
53	Nutwood, IL	Residential	Riverine	Summer 1993	Elevation--extended foundation walls	Failed
54	Nutwood, IL	Residential	Riverine	Summer 1993	Elevation--extended foundation walls	Failed
55	Nutwood, IL	Residential	Riverine	Summer 1993	Elevation--extended foundation walls	Failed
56	Herman, MO	Industrial	Riverine	Summer 1993	Floodwall	Failed
Structure No.	Community	Structure Type	Flood Source	Flood Date	Flood Proofing Measure	Performance
57	Ames, IA	Public	Riverine	Jul 1993	Dry Flood proofing w/closures	Failed

TABLE 1 (cont.)

58	Ames, IA	Public	Riverine	Jul 1993	Elevation	Failed
59	Houston, TX	Residential	Riverine	Fall 1994	Elevation--wood posts	Failed
60	Houston, TX	Residential	Riverine	Fall 1994	Elevation--wood posts	Successful
61	Houston, TX	Residential	Riverine	Fall 1994	Elevation--wood posts	Failed
62	Houston, TX	Residential	Riverine	Fall 1994	Elevation--wood posts	Successful
63	Houston, TX	Residential	Riverine	Fall 1994	Elevation--wood posts	Successful
64	Houston, TX	Residential	Riverine	Fall 1994	Elevation--masonry columns	Successful
65	Houston, TX	Residential	Riverine	Fall 1994	Elevation--wood posts	Failed
66	Houston, TX	Residential	Riverine	Fall 1994	Elevation--wood posts	Failed
67	Houston, TX	Residential	Riverine	Fall 1994	Elevation--extended foundation walls	Failed
68	Houston, TX	Residential	Riverine	Fall 1994	3>	Failed
69	Houston, TX	Residential	Riverine	Fall 1994	3>	Failed
70	Houston, TX	Residential	Riverine	Fall 1994	3>	Failed
71	Houston, TX	Residential	Riverine	Fall 1994	3>	Failed
Structure No.	Community	Structure Type	Flood Source	Flood Date	Flood Proofing Measure	Performance
72	Panama City, FL	Residential	Coastal	Fall 1995	Elevation--extended foundation walls with seawall	Failed

TABLE 1 (cont.)

73	Panama City, FL	Residential	Coastal	Fall 1995	Elevation--extended foundation walls with seawall	Failed
74	Panama City, FL	Residential	Coastal	Fall 1995	Elevation--extended foundation walls	Failed
75	Panama City, FL	Residential	Coastal	Fall 1995	Elevation--extended foundation walls	Failed
76	Panama City, FL	Residential	Coastal	Fall 1995	Elevation--wood piles	Failed
77	Panama City, FL	Residential	Coastal	Fall 1995	Elevation--extended foundation walls	Failed
78	Panama City, FL	Residential	Coastal	Fall 1995	Elevation--wood piles	Failed
79	Panama City, FL	Residential	Coastal	Fall 1995	Elevation--extended foundation walls	Failed
80	Panama City, FL	Residential	Coastal	Fall 1995	Elevation--wood piles	Failed
Structure No.	Community	Structure Type	Flood Source	Flood Date	Flood Proofing Measure	Performance
81	Panama City, FL	Residential	Coastal	Fall 1995	Elevation	Successful

TABLE 1 (cont.)

Structure No.	Community	Structure Type	Flood Source	Flood Date	Flood Proofing Measure	Performance
82	Panama City, FL	Residential	Coastal	Fall 1995	Elevation--masonry columns with seawall	Successful
83	Panama City, FL	Motel	Coastal	Fall 1995	Elevation--wood piles	Successful
84	Panama City, FL	Residential	Coastal	Fall 1995	Sand dune	Successful
85	Pensacola, FL	Residential	Coastal	Fall 1995	Elevation--wood frame	Failed
86	Pensacola, FL	Residential	Coastal	Fall 1995	Elevation--wood piles	Successful
87	Pensacola, FL	Residential	Coastal	Fall 1995	Elevation--wood piles	Successful
88	Pensacola, FL	Residential	Coastal	Fall 1995	Elevation--concrete columns	Successful
89	Pensacola, FL	Residential	Coastal	Fall 1995	Elevation--wood piles	Successful
90	Sacramento, CA	Residential	Riverine	Jan 1997	Floodwall	Failed
91	Sacramento, CA	Residential	Riverine	Jan 1997	Levee	Failed
92	Reno, NV	Public	Riverine	Jan 1997	Wet/dry flood proofing	Failed
93	Reno, NV	Commerical	Riverine	Jan 1997	Elevation--fill	Successful

TABLE 1 (cont.)

94	Reno, NV	Commerical	Riverine	Jan 1997	Levee	Successful
95	Reno, NV	Commerical	Riverine	Jan 1997	Levee	Successful
96	Ashland, NE	Public	Riverine	Feb 1997	Elevation	Successful
97	East Grand Forks, MN	Residential	Riverine	Apr 1997	Dry flood proofing	Failed
98	Oakport, MN	Residential	Riverine	Apr 1997	Dry flood proofing	Successful

1> Ten structures are represented, 7 of which were damaged and 3 were not damaged.

2> This structure represents the numerous single-family homes and small commerical buildings that are elevated on piles, posts(columns), piers, extended foundations, etc.

3> The structures were so totally destroyed that the flood proofing measure used could not be identified by observation.

TABLE 2

SUMMARY OF FLOOD PROOFING PERFORMANCE
(Organized by Flood Proofing Measure)

Structure No.	Flood Proofing Measure	Structure Type	Flood Source	Flood Date	Community	Performance
14	Dry flood proofing	Residential	Riverine	Jun 1989	Montgomery Co., TX	Successful
16	Dry flood proofing	Residential	Riverine	May 1989	Montgomery Co., TX	Partially Successful
10	Dry flood proofing	Residential	Riverine	Jul 1987	Crystal, MN	Failed
2	Dry flood proofing	Commercial	Riverine	Sep 1986	Alma, MI	Overtopped
4	Dry flood proofing	Residential	Riverine	Sep 1986	Midland, MI	Failed
6	Dry flood proofing	Residential	Riverine	Sep 1986	Midland, MI	Failed
7	Dry flood proofing	Residential	Riverine	Sep 1986	Midland, MI	Failed
1	Dry flood proofing	Residential	Riverine	Sep 1986	Clive, IA	Successful
57	Dry flood proofing w/closures	Public	Riverine	Jul 1993	Ames, IA	Failed

TABLE 2 (cont.)

Structure No.	Flood Proofing Measure	Structure Type	Flood Source	Flood Date	Community	Performance
97	Dry flood proofing	Residential	Riverine	Apr 1997	East Grand Forks, MN	Failed
98	Dry flood proofing	Residential	Riverine	Apr 1997	Oakport, MN	Successful
3	Dry Flood proofing	Residential	Riverine	Sep 1986	Midland, MI	1>
5	Dry Flood proofing	Residential	Riverine	Sep 1986	Midland, MI	Failed
13	Earthen ring levee/ elevation--extended foundation walls	Residential	Riverine	Jun 1989	Montgomery Co., TX	Successful
51	Elevation 2>	Residential	Riverine	Summer 1993	St. Louis, MO	Failed
52	Elevation--extended foundation walls	Residential	Riverine	Summer 1993	Nutwood, IL	Failed
58	Elevation	Public	Riverine	Jul 1993	Ames, IA	Failed
81	Elevation	Residential	Coastal	Fall 1995	Panama City, FL	Successful
93	Elevation--fill	Commerical	Riverine	Jan 1997	Reno, NV	Successful
96	Elevation	Public	Riverine	Feb 1997	Ashland, NE	Successful

TABLE 2 (cont.)

Structure No.	Flood Proofing Measure	Structure Type	Flood Source	Flood Date	Community	Performance
20	Elevation--block piers	Residential	Coastal	Sep 1989	Surfside Beach, C	Failed
19	Elevation--brick piers	Residential	Coastal	Sep 1989	Surfside Beach, SC	Failed
25	Elevation--concrete piles	Residential	Coastal	Sep 1989	Pawley's Island, SC	Failed
27	Elevation--concrete piers	Residential	Coastal	Sep 1989	Debidue Beach, SC	Failed
88	Elevation--concrete columns	Residential	Coastal	Fall 1995	Pensacola, FL	Successful
46	Elevation--extended foundation walls	Residential	Riverine	Summer 1993	Barnhart, MO	Failed
53	Elevation--extended foundation walls	Residential	Riverine	Summer 1993	Nutwood, IL	Failed
54	Elevation--extended foundation walls	Residential	Riverine	Summer 1993	Nutwood, IL	Failed
55	Elevation--extended foundation walls	Residential	Riverine	Summer 1993	Nutwood, IL	Failed
67	Elevation--extended foundation walls	Residential	Riverine	Fall 1994	Houston, TX	Failed

TABLE 2 (cont.)

Structure No.	Flood Proofing Measure	Structure Type	Flood Source	Flood Date	Community	Performance
72	Elevation--extended foundation walls with seawall	Residential	Coastal	Fall 1995	Panama City, FL	Failed
73	Elevation--extended foundation walls with seawall	Residential	Coastal	Fall 1995	Panama City, FL	Failed
74	Elevation--extended foundation walls	Residential	Coastal	Fall 1995	Panama City, FL	Failed
75	Elevation--extended foundation walls	Residential	Coastal	Fall 1995	Panama City, FL	Failed
77	Elevation--extended foundation walls	Residential	Coastal	Fall 1995	Panama City, FL	Failed
79	Elevation--extended foundation walls	Residential	Coastal	Fall 1995	Panama City, FL	Failed
50	Elevation--fill	Commercial	Riverine	Summer 1993	St. Genevieve, MO	Successful
28	Elevation--masonry piers	Residential	Coastal	Sep 1989	Charleston Co., SC	Failed

TABLE 2 (cont.)

Structure No.	Flood Proofing Measure	Structure Type	Flood Source	Flood Date	Community	Performance
29	Elevation--masonry piers	Residential	Coastal	Sep 1989	Charleston Co., SC	Successful
30	Elevation--masonry piers	Residential	Coastal	Sep 1989	Charleston Co., SC	Successful
37	Elevation--masonry columns/wood piles	Residential	Coastal	Sep 1989	Charleston Co., SC	Successful
38	Elevation--concrete block columns	Residential	Coastal	Sep 1989	Charleston Co., SC	Failed
64	Elevation--masonry columns	Residential	Riverine	Fall 1994	Houston, TX	Successful
82	Elevation--masonry columns/seawall	Residential	Coastal	Fall 1995	Panama City, FL	Successful
26	Elevation--piles	Residential	Coastal	Sep 1989	Debidue Beach, SC	Failed
40	Elevation--reinforced concrete columns	Residential	Coastal	Sep 1989	Charleston Co., SC	Successful
18	Elevation--steel columns	Residential	Coastal	Sep 1989	Surfside Beach, SC	Successful
17	Elevation--wood piles	Residential	Riverine	Jun 1989	Montgomery Co., TX	Successful

TABLE 2 (cont.)

Structure No.	Flood Proofing Measure	Structure Type	Flood Source	Flood Date	Community	Performance
21	Elevation--wood piles	Residential	Coastal	Sep 1989	Garden City, SC	Successful
22	Elevation--wood piles	Residential	Coastal	Sep 1989	Garden City, SC	Successful
23	Elevation--wood columns	Residential	Coastal	Sep 1989	Pawley's Island, SC	Failed
24	Elevation--wood columns	Residential	Coastal	Sep 1989	Pawley's Island, SC	Successful
31	Elevation--wood piles	Residential	Coastal	Sep 1989	Charleston Co., SC	Successful
32	Elevation--wood piles	Residential	Coastal	Sep 1989	Charleston Co., SC	Successful
33	Elevation--wood posts	Residential	Coastal	Sep 1989	Charleston Co., SC	Successful
34	Elevation--wood piles	Residential	Coastal	Sep 1989	Charleston Co., SC	Failed
35	Elevation--wood piles	Residential	Coastal	Sep 1989	Charleston Co., SC	Failed
36	Elevation--wood piles	Residential	Coastal	Sep 1989	Charleston Co., SC	Failed
39	Elevation--wood posts	Residential	Coastal	Sep 1989	Charleston Co., SC	Successful
41	Elevation--wood piles	Residential	Coastal	Sep 1989	Charleston Co., SC	Successful
42	Elevation--wood piles	Residential	Coastal	Sep 1989	Charleston Co., SC	Failed
59	Elevation--wood posts	Residential	Riverine	Fall 1994	Houston, TX	Failed

TABLE 2 (cont.)

Structure No.	Flood Proofing Measure	Structure Type	Flood Source	Flood Date	Community	Performance
60	Elevation--wood posts	Residential	Riverine	Fall 1994	Houston, TX	Successful
61	Elevation--wood posts	Residential	Riverine	Fall 1994	Houston, TX	Failed
62	Elevation--wood posts	Residential	Riverine	Fall 1994	Houston, TX	Successful
63	Elevation--wood posts	Residential	Riverine	Fall 1994	Houston, TX	Successful
65	Elevation--wood posts	Residential	Riverine	Fall 1994	Houston, TX	Failed
66	Elevation--wood posts	Residential	Riverine	Fall 1994	Houston, TX	Failed
76	Elevation--wood piles	Residential	Coastal	Fall 1995	Panama City, FL	Failed
78	Elevation--wood piles	Residential	Coastal	Fall 1995	Panama City, FL	Failed
80	Elevation--wood piles	Residential	Coastal	Fall 1995	Panama City, FL	Failed
83	Elevation--wood piles	Motel	Coastal	Fall 1995	Panama City, FL	Successful
85	Elevation--wood frame	Residential	Coastal	Fall 1995	Pensacola, FL	Failed
86	Elevation--wood piles	Residential	Coastal	Fall 1995	Pensacola, FL	Successful
87	Elevation--wood piles	Residential	Coastal	Fall 1995	Pensacola, FL	Successful
89	Elevation--wood piles	Residential	Coastal	Fall 1995	Pensacola, FL	Successful

TABLE 2 (cont.)

Structure No.	Flood Proofing Measure	Structure Type	Flood Source	Flood Date	Community	Performance
15	Floodwall	Residential	Riverine	May 1989	Montgomery Co., TX	Overtopped
8	Floodwall	Residential	Riverine	Jul 1987	Crystal, MN	Failed
9	Floodwall	Residential	Riverine	Jul 1987	Crystal, MN	Mostly Successful
11	Floodwall	Residential	Riverine	Jul 1987	Crystal, MN	Failed
12	Floodwall	Residential	Riverine	Jul 1987	Crystal, MN	Failed
44	Floodwall	Residential/ Commercial	Riverine	Summer 1993	Herculaneum, MO	Failed
45	Floodwall	Residential	Riverine	Summer 1993	Barnhart, MO	Failed
47	Floodwall	Commercial Government	Riverine	Summer 1993	St. Louis, MO	Failed
56	Floodwall	Industrial	Riverine	Summer 1993	Herman, MO	Failed
90	Floodwall	Residential	Riverine	Jan 1997	Sacramento, CA	Failed

TABLE 2 (cont.)

Structure No.	Flood Proofing Measure	Structure Type	Flood Source	Flood Date	Community	Performance
43	Levee	Industrial/ Commercial	Riverine	Summer 1993	Crystal City, MO	Failed
48	Levee	Commercial	Riverine	Summer 1993	St. Genevieve, MO	Successful
91	Levee	Residential	Riverine	Jan 1997	Sacramento, CA	Failed
94	Levee	Commerical	Riverine	Jan 1997	Reno, NV	Successful
95	Levee	Commerical	Riverine	Jan 1997	Reno, NV	Successful
84	Sand dune	Residential	Coastal	Fall 1995	Panama City, FL	Successful
49	Wet flood proofing	Commercial	Riverine	Summer 1993	St. Genevieve, MO	Failed
92	Wet/dry flood proofing	Public	Riverine	Jan 1997	Reno, NV	Failed
68	3>	Residential	Riverine	Fall 1994	Houston, TX	Failed

TABLE 2 (cont.)

Structure No.	Flood Proofing Measure	Structure Type	Flood Source	Flood Date	Community	Performance
69	3>	Residential	Riverine	Fall 1994	Houston, TX	Failed
70	3>	Residential	Riverine	Fall 1994	Houston, TX	Failed
71	3>	Residential	Riverine	Fall 1994	Houston, TX	Failed

1> Ten structures are represented, 7 of which were damaged and 3 were not damaged.

2> This structure represents the numerous single-family homes and small commerical buildings that are elevated on piles, posts(columns),piers, extended foundations, etc.

3> The structures were so totally destroyed that the flood proofing measure used could not be identified by observation.

CHAPTER 4 - DO'S AND DON'TS OF FLOOD PROOFING

Flood proofing is a very viable option to reduce or eliminate flood damages. As discussed in Chapter 1, where flood proofing measures are described and as demonstrated in Chapter 2, where applied flood proofing measures are analyzed, flood proofing can be accomplished by various basic measures and many varying forms of these measures. Successful flood proofing is complex in that many items are involved and all items must function properly. Chapter 2 demonstrates this on a case by case basis. Chapter 2 also demonstrates the converse--unsuccessful flood proofing most often is due to a simple item or two that are either overlooked in the flood proofing measure design or are not designed properly, leading to failure of the item or items and subsequent failure of the entire flood proofing system. Listed below are those items that have been found to be critical to success or failure of the flood proofing measure--the "do's and don'ts" of flood proofing..

1. Do install an internal drainage system as an integral part of any dry, levee, or floodwall flood proofing measure. The drainage system must be adequate to evacuate water accumulated in the protected areas not only from seepage through or under the flood proofing measure but also from rainfall within the protected area. The drainage system must also be large enough to reduce hydrostatic force if dry flood proofing is used to flood proof a basement.

2. Do design floodshields and closures to withstand the same flood-related forces as the basic flood proofing measure.

3. Do remember that flood proofing measures that are barriers (levees, floodwalls, and dry measures) can be overtopped. When this occurs, damages happen that are equal to, if not worse than, those that would occur if the flood proofing measure was not present. A false sense of security can develop. Freeboard should be included as a factor of safety.

4. Do remember that floodshields that span large lengths need lateral bracing, such as diagonal bracing from the top of the floodshield to the floor, to withstand hydrostatic force. All free-standing walls intended to resist hydrostatic force must be reinforced and tied to a proper foundation. All floodshields that span openings 3 feet or greater should be made of metal construction for strength and rigidity.

5. Do design all foundations to be supported to depths greater than any anticipated scour.

6. Do direct sump pump discharge from the protected area well away from the flood proofed structure.

7. Do make certain that all utility entry points through the flood proofing system are properly sealed, and have check valves installed in sewer lines.

8. Don't dry flood proof a structure that has a full basement with nonreinforced walls and floor. If an exception is ever made to this rule, it could only be made if the flood is of very short duration, the soil is not permeable, and the floodwater does not come in contact with the structure. The best alternative is wet flood proofing if sufficient time exists either to flood the basement with clear water prior to the flood or to break up the basement floor and permanently fill the basement with gravel.

9. Do design an internal drainage system using a sump pump with a "backup" power supply consisting of batteries or a generator in case utility electric power fails or is purposely disconnected.

10. Don't use elevation on extended foundation walls in moderate-to high-velocity areas, in areas subject to ice and debris flows, or in areas subject to storm surge.

11. Do remember that structures having full basements with walls designed to resist hydrostatic force must also have the floor reinforced to resist uplift due to hydrostatic force.

12. Don't attempt to dry flood proof basements unless no other alternative exists. Reliable dry flood proofing of basements is extremely difficult to attain due to the hydrostatic force that can cause wall and floor failure or structure buoyancy. If dry flood proofing a basement is employed, be sure to install designer "blowout plugs" that will fail prior to total floor and wall failure or buoyancy.

13. Do remember that the best practice in areas where basements are considered essential is to construct the basements partially above existing grade and then to place fill around the basement walls. This elevates the structure without the visual appearance of elevating, and it lowers the amount of hydrostatic force that can act on the basement walls during flood events. In order to give the highest degree of reliability, the soil surrounding the basement must be highly impermeable and the design flood must not come in contact with the basement walls. Floods of long duration are much more difficult to dry flood proof against than those of short duration.

14. Do place perimeter footings deeper than the expected scour depth around a concrete slab-on-grade to prevent scour beneath the slab and slab failure.

15. Don't enclose lower areas of raised structures with rigid (nonbreakaway) walls in high-velocity areas.

16. Do enclose lower areas of raised structures with "jail-type" flow-through walls in high-

velocity areas.

17. Don’t place shallow embedded concrete footings to support elevated structures in coastal areas subject to hurricane forces or in riverine areas subject to high velocities.

18. Don’t use metal fasteners to tie structural members together unless they are made of corrosion-resistant material. Protect these fastners from salt water and inspect them annually for corrison where possible.

19. Do always use piles as a foundation in areas subject to erosion and scour.

20. Don’t use piers in coastal or riverine areas subject to scour. The footings of this type of foundation are simply too shallow to reliably resist scour.

21. Do develop and maintain a well-vegetated dune system, if possible, to protect from storm surge and scour in coastal areas.

22. Do minimize the amount of obstruction beneath an elevated structure in hurricane and high-velocity riverine areas.

23. Do encapsulate utility duct work beneath elevated structures in plywood to make the duct work less prone to damage from storm surge in hurricane areas.

24. Do remember that in hurricane areas simple things like orienting the floor joists of an elevated structure parallel to the storm surge can prevent damage.

25. Do remember that riprap placed along a beach to provide erosion protection can be removed by hurricane storm surges and driven into coastal structures, creating damage.

26. Do remember in coastal areas to wind proof as well as flood proof a structure.

27. Don’t construct levees with sideslopes steeper than 1 vertical to 2 horizontal. A sideslope of 1 vertical to 3 horizontal is preferable.

28. Do relocate from the flood plain whenever possible.

29. Don’t remain in a flood proofed structure during a flood event. Staying in a structure to fight the flood results in trading a reduction in flood damages by human intervention with increasing the

potential for loss of life.

30. Do shut off natural gas or propane utilities to a flood proofed structure in preparation for the flood event. Electricity should be shut off if possible if it is not needed to make the flood proofing system functional. Fires do occur in flooded areas because of electrical “shorts” and gas line ruptures.

31. Don’t forget to take into account the structural integrity of the building when considering flood proofing.

32. Don’t forget to take into consideration the size of footings supporting a floodwall and their ability to resist tipping when adding height either permanently to a floodwall or temporarily during a flood fight.

33. Don’t forget to “practice” each flood proofing system that requires human intervention on an annual basis.

34. Do consider establishing a stand of trees and bushes upstream from the flood proofed structures in potential high-velocity areas to shield the structures from high velocities and floating debris.

35. Don’t place flood plain obstructions beneath elevated structures with slabs-on- grade at the upstream edge of the slab in high-velocity areas.

36. Do place concrete around posts used to elevate structures to enhance stability.

37. Don’t construct or flood proof structures in areas that are subject to such extremely high velocities that no feasible structure can survive.

38. Do employ seawalls in coastal areas to protect beachfront property from severe erosion.

39. Don’t construct slab-on-grade floors in coastal or riverine areas where scour beneath the floors is possible without placing perimeter footings to depths greater than potential scour.

40. Do extend piles, piers, posts, and columns from the structural foundation through the floor to the roofline for proper tie-in of the structure to the foundation in coastal areas.

41. Don’t orient the long dimension of a structure perpendicular to floodflows or storm surge.

42. Don’t employ dry flood proofing measures on normally built structures expecting more than

3 feet of water on the walls.

43. Don't use dry flood proofing measures in moderate-to high-velocity areas or in areas subject to ice and debris flow.

44. Do have floodshields for closures readily accessible.

45. Do practice installing floodshields for closures during nonflood periods.

46. Do install a "factor of safety" in those flood proofing measures that can be overtopped.

47. Don't forget to consider the effects of hydrostatic force on basement floors or slabs-on-grade when using dry flood proofing.

48. Don't use a flood proofing measure that requires human intervention in a flash flood area. Always consider the amount of warning time available prior to flooding.

49. Do remember to periodically check the caulking and sealants that make a dry flood proofing measure successful.

50. Do seek professional help from engineers, contractors, and so forth before implementing flood proofing.

51. Don't forget that all flood proofing measures require maintenance after implementation to ensure success.

52. Do purchase flood insurance for flood proofed structures and contents.

53. Do design an anti-buoyancy mechanism to keep a dry flood proofed structure from floating during a flood because of hydrostatic forces.

54. Do compact backfill placed under floodwalls where excavations have been made for utilities to prevent piping.

55. Do design redundancy into a sump pump system so the system can continue to operate without human intervention and without electrical power from a powerline source. Generators or battery backup is required.

56. Do remember that all flood proofing systems are only as good as the weakest part of the system.

57. Do use reinforced concrete in dry flood proofing rather than concrete blocks with steel reinforcement.

58. Do remember that areas subject to ice or debris/mudflows require special flood proofing system designs to withstand forces associated with these hazards.

59. Do install floodshields so hydrostatic force will make the seal tighter. Always install a seal around the edge of the floodshield.

60. Do consider elevating a structure as high as possible to provide the most flood protection. Costs to elevate several feet are normally not much more than elevating one or two feet. The only exception to this are in those cases where wind and/or seismic forces cause costs to increase as structure elevation height becomes greater.

61. Don’t use posts or columns that require cross bracing for structure support in areas that are subject to ice or debris and hydrodynamic force.

CHAPTER 5 - GLOSSARY

Beach	The strip of land that directly abuts the water's edge of an ocean or lake.
Berm	A bank or mound of compacted earth, usually placed against a foundation wall.
Blowout Plug	A designed "weak" spot in a basement wall or floor that will fail first due to hydrostatic force, thus preventing total failure of the wall or floor.
Borrow Area	An area where material has been excavated for use as fill at another location.
Building Code	Regulations adopted by local governments that establish standards for construction, modification, and repair of buildings and other structures.
Buoyancy	Forces that cause a structure to float.
Caulking	Flexible material used to fill joints in a structure, such as around windows or doors, which is able to resist the passage of moisture.
Check Valve	A type of valve that allows water to flow one way but automatically closes when water attempts to flow in the opposite direction.
Closure	A shield made of strong material, such as steel, aluminum, or wood, used to temporarily fill gaps in floodwalls, levees, or dry flood proofed structures and protect against water entrance through areas that have been left open for day-to-day convenience at entrances such as doors and driveways.
Column	An upright support unit for a structure that is set in predug holes and backfilled with compacted material. Columns are usually of concrete or masonry construction with steel reinforcement. Columns are sometimes referred to as posts.
Crawl Space	The area between the ground surface and the bottom of the first floor of an elevated structure. The structure is elevated a minimal distance above the ground so access under the structure is by crawling.

Debris Flow See Mudflow.

Debris Impact Sudden loads induced on a structure by debris carried by floodwater.

Dry Flood Proofing A method used in areas of low-level flooding to completely seal a structure against water by making the structure substantially impermeable to the passage of water.

Elevation The raising of a structure to place the lowest floor at or above the flood protection elevation on an extended support structure.

Erosion The action of moving water against soil where the soil particles are translocated by the moving water to another location.

Event An occurrence of flooding.

Extended Foundation Wall The construction of an additional wall to gain height above the existing foundation walls in order to elevate a structure to or above the design flood elevation.

Fill Material such as earth, clay, or crushed stone that is placed in an area and compacted to increase ground elevation.

Flash Flood A flood that crests in a short length of time and is often characterized by high-velocity flow. It is often the result of heavy rainfall in a localized area.

Flood A partial or complete inundation of normally dry land areas from the overland flow of a lake, ocean, river, stream, ditch, etc.

Flood Crest The maximum height of a flood event at a particular location.

Flood Depth The height difference between the flood elevation and the lowest grade adjacent to the structure.

Floodflow A term used to refer to the movement of floodwater.

Floodshield See Closure.

Floodwall	A constructed barrier of resistant material, such as concrete or masonry block, designed to keep water away from a structure.
Footings	The enlarged base of a foundation wall, pier, or column designed to spread the load of the structure so that it does not exceed the soil-bearing capacity.
Foundation Wall	A support structure that connects the foundation (the building substructure) to the main portion of the building (the building superstructure).
Freeboard	An additional amount of height used as a factor of safety in determining the design height of a flood protection measure to compensate for unknown factors such as wave action, the hydrologic effect of urbanization, etc.
Grade	The elevation of ground adjacent to a structure.
Grouting	The practice of filling the holes in concrete blocks with concrete to increase the strength of a concrete block floodwall.
Human Intervention	The required presence and active involvement of people to enact any type of flood proofing measure prior to flooding.
Hydrodynamic Force	Forces imposed on an object, such as a structure, by water moving around it. Among these loads are positive frontal pressure against the structure, drag effect along the sides, and negative pressure on the downstream side.
Hydrostatic Force	Forces imposed on a surface, such as a wall or floor slab, by a standing mass of water. The force increases with increasing water depth.
Interior Grade Beam	A section of a floor slab that has a thicker section of concrete to act as footings to provide stability under load-bearing or critical structural walls.
Internal Drainage	Water that enters a protected area by rainfall or seepage.
Levee	A barrier of compacted soil designed to keep floodwater away from a structure.

Loads	Forces imposed on a surface such as a wall or floor, an entire structure, or on the ground.
Lower Area	The area that exists between the elevated floor and “grade” of an elevated structure.
Measure	This refers to an individual flood proofing method.
Mud Flooding	Floodflows that contain sediment and debris to such an extent that the sediment and debris “solids” by volume range between 20 and 45 percent of the total floodflow volume.
Mudflow	Floodflows that contain sediment and debris to such large extent that the sediment and debris “solids” by volume exceed 45 percent of the total floodflow volume. The “debris” can contain extremely large boulders that can be floated by this type of floodflow.
Moment	The product of a force and its perpendicular distance from its axis.
Perimeter Footing	A wall made of concrete that projects downward from the edge of a concrete slab into the earth.
Permeability	The property of soil or rock that allows water to pass through it.
Pier	An upright support member of a building that is designed andconstructed to function as an independent structural element in supporting and transmitting building and environmental loads to the ground.
Pile	An upright support member of a building that is usually long andslender in shape, driven or jetted into the ground by mechanical means, and primarily supported by friction between the pile and the surrounding earth.
Piping	The passage of water through an embankment of earth that beginsextremely slow with gradual wetting of the earth and proceeds to increase gradually in flow until flood protection failure occurs.

Post	A long, upright support unit for a building that is set in predug holes and backfilled with compacted material. Each post usually requires bracing toother units. Posts are also known as columns, although posts are usually made of wood.
Protected Area	That area protected from flooding by a flood proofing measure such as a levee or floodwall.
Rebar	Steel rods that are placed inside poured concrete and become an integral part of the concrete to give it added strength.
Relocation	Moving a structure from a flood-prone area to a new location, normally to one where there is no threat of flooding.
Riprap	Broken stone, cut stone blocks, or rubble that is placed on slopes to protect the slopes from erosion or scour caused by floodwaters or wave action.
Scour	The localized erosion around floodflow obstructions caused by the movement of soil or sediment by high-velocity water.
Seepage	Water that leaks through or under a flood proofing measure such as a levee or floodwall.
Slab-on-Grade	A structural design where the first floor is located on a poured concrete slab that sits directly on the ground.
Spread Footing	See Footings.
Storm Surge	The maximum water surface elevation in coastal areas resulting from hurricane force winds driving ocean water upward over areas above mean sea level.
System	A combination of flood proofing measures.
Wave Runup	See Storm Surge.